Keysight Technologies

3GPP Long Term Evolution: System Overview, Product Development, and Test Challenges

Application Note

3GPP LTE standard
Release 8/Release 9

Introduction

This application note describes the Long Term Evolution (LTE) of the universal mobile telecommunication system (UMTS) standard by the 3rd Generation Partnership Project (3GPP). Particular attention is given to LTE's use of multiple antenna techniques and to the modulation scheme called single carrier frequency division multiple access (SC-FDMA) used in the LTE uplink. This application note covers the core LTE specifications defined in 3GPP Releases 8 and 9; it does not include the LTE-Advanced specifications, which are defined in 3GPP Release 10 and beyond. Because LTE is now on the market and the pace of LTE product development has accelerated, measurement tools are needed that can handle the complexities and technical challenges introduced by the standard. Keysight Technologies, Inc. comprehensive portfolio of LTE design, verification, and test solutions is introduced in this context.

Table of Contents

1. LTE Concepts

1.1 Introduction

Third-generation UMTS, based on wideband code-division multiple access (W-CDMA), has been deployed all over the world. To ensure that this system remains competitive in the future, in November 2004 3GPP began a project to define the long-term evolution of UMTS cellular technology. The specifications related to this effort are formally known as the evolved UMTS terrestrial radio access (E-UTRA) and evolved UMTS terrestrial radio access network (E-UTRAN), but are more commonly referred to by the project name LTE. The first version of LTE is documented in Release 8 of the 3GPP specifications.

A parallel 3GPP project called System Architecture Evolution (SAE) defines an all-IP, packet-only core network known as the evolved packet core (EPC). The combination of the EPC and the evolved RAN (E-UTRA plus E-UTRAN) is the evolved packet system (EPS). Depending on the context, any of the terms LTE, E-UTRA, E-UTRAN, SAE, EPC and EPS may get used to describe some or all of the system. Although EPS is the correct term for the overall system, the name of the system will sometimes be written as LTE/SAE or simply LTE.

3GPP's high-level requirements for LTE include reduced cost per bit, better service provisioning, flexible use of new and existing frequency bands, simplified network architecture with open interfaces, and an allowance for reasonable power consumption by terminals. These are detailed in the LTE feasibility study, 3GPP Technical Report 25.912 [1], and in the LTE requirements document, 25.913 [2].

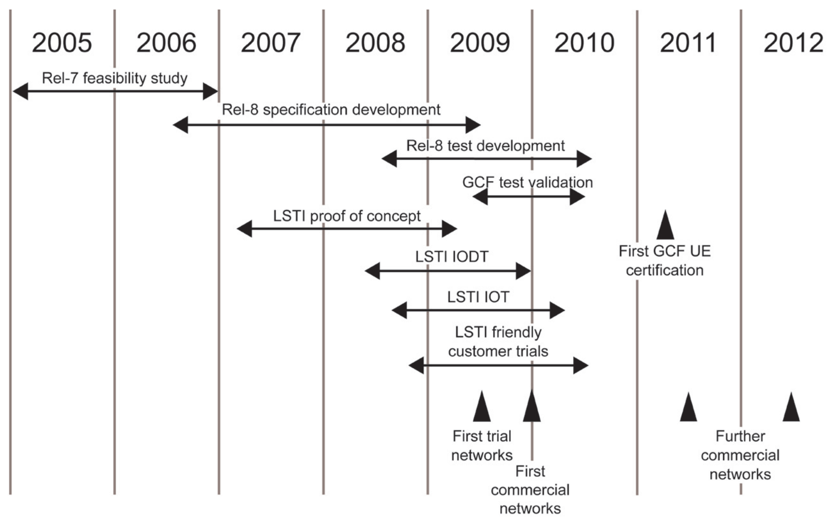

Figure 1. LTE development lifecycle

LTE development, shown in Figure 1, includes the work of 3GPP in drafting the specifications along with the conformance test activities of the Global Certification Forum (GCF) and the trials carried out by the LTE/SAE Trial Initiative (LSTI). The LSTI is an industry forum and complimentary group who are working in parallel with 3GPP and GCF with the intent of accelerating the acceptance and deployment of LTE/SAE as the logical choice of the industry for next-generation networks.

The LSTI completed its friendly customer trials in 2010. GCF certified the first UE against the 3GPP conformance tests in April 2011. By May 2013 there were 175 commercial LTE networks operating in 70 countries according to the Global Suppliers Association.

1.2 Summary of LTE requirements

To meet the requirements for LTE outlined in 25.913, LTE aims to achieve the following:

- Increased downlink and uplink peak data rates, as shown in Table 1. Note that the downlink is specified for single input single output (SISO) and multiple input multiple output (MIMO) antenna configurations at a fixed 64QAM modulation depth, whereas the uplink is specified only for SISO but at different modulation depths. These figures represent the physical limitation of the frequency division duplex (FDD) air interface in ideal radio conditions with allowance for signaling overheads. Lower rates are specified for specific UE categories, and performance requirements under non-ideal radio conditions have also been developed. Comparable figures exist in 25.912 for TDD.
- Scalable channel bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz in both the uplink and the downlink
- Spectral efficiency improvements over Release 6 high speed packet access (HSPA) of three to four times in the downlink and two to three times in the uplink
- Sub-5 ms latency for small internet protocol (IP) packets
- Performance optimized for low mobile speeds from 0 to 15 km/h, supported with high performance from 15 to 120 km/h; functional support from 120 to 350 km/h, under consideration for 350 to 500 km/h
- Co-existence with legacy standards while evolving toward an all-IP network

Table 1. LTE (FDD) downlink and uplink peak data rates from 25.912 Tables 13.1 and 13.1a

FDD downlink peak data rates (64QAM)			
Antenna configuration	SISO	2x2 MIMO	4x4 MIMO
Peak data rate Mbps	100	172.8	326.4
FDD uplink peak data rates (single antenna)			
Modulation depth	QPSK	16QAM	64QAM
Peak data rate Mbps	50	57.6	86.4

1.3 History of the UMTS standard

Table 2 summarizes the evolution of the 3GPP UMTS specifications towards LTE. Each release of the 3GPP specifications represents a defined set of features. A summary of the contents of any release can be found at www.3gpp.org/releases. The date given for the functional freeze relates to the date when no further new items can be added to the release. Any further changes to the specifications are restricted to essential corrections.

After Release 99, 3GPP stopped naming releases after the year and opted for a new scheme that started with Release 4. Release 4 introduced the 1.28 Mcps narrow band version of W-CDMA, also known as time domain synchronous code division multiple access (TD-SCDMA). Following this was Release 5, in which high speed downlink packet access (HDSPA) introduced packet-based data services to UMTS in the same way that the general packet radio service (GPRS) did for GSM in Release 97 (1998). The completion of packet data for UMTS was achieved in Release 6 with the addition of high speed uplink packet access (HSUPA), although the official term for this technology is enhanced dedicated channel (E-DCH). HSDPA and HSUPA are now known collectively as high speed packet access (HSPA). Release 7 contained the first work on LTE/SAE with the completion of the feasibility studies, and further improvements were made to HSPA such as downlink MIMO, 64QAM on the downlink, and 16QAM on the uplink.

In Release 8, HSPA continued to evolve with the addition of numerous smaller features such as dual cell HSDPA and 64QAM with MIMO. The main work in Release 8, however, is the specification of LTE and SAE. Release 9 further enhances LTE. Release 10 and beyond put forward LTE-Advanced, a technology approved for the International Telecommunications Union (ITU) IMT-Advanced program, better known as 4G.

Table 2. Evolution of the UMTS specifications

Release	Functional freeze	Main UMTS feature of release
Rel-99	March 2000	Basic 3.84 Mcps W-CDMA (FDD & TDD)
Rel-4	March 2001	1.28 Mcps TDD (also called TD-SCDMA)
Rel-5	June 2002	HSDPA
Rel-6	March 2005	HSUPA (E-DCH)
Rel-7	December 2007	HSPA+ (64QAM downlink, MIMO, 16QAM uplink), LTE and SAE feasibility study, EDGE evolution
Rel-8	December 2008	LTE work item – OFDMA/SC-FDMA air interface SAE work item – new IP core network UMTS femtocells, dual-carrier HSDPA
Rel-9	December 2009	Multi-standard radio (MSR), dual-carrier HSUPA, dual-band HSDPA, SON, LTE femtocells (HeNB), LTE-Advanced feasibility study
Rel-10	March 2011	LTE-Advanced (4G) work item, CoMP study, four-carrier HSDPA
Rel-11	September 2012	CoMP, eDL MIMO, eCA, MIMO OTA, HSUPA TxD and 64QAM MIMO, HSDPA 8C and 4x4 MIMO, MB MSR
Rel-12	March 2013 stage 1	RAN features decided June 2012

There are other standardization activities within 3GPP not shown in Table 2 such as those for the GSM Enhanced RAN (GERAN) and the Internet Protocol Multimedia Subsystem (IMS).

1.4 LTE in context

3GPP LTE is one of several evolved 3G wireless standards. The other standards are as follows:

- 3GPP HSPA+
- 3GPP EDGE Evolution
- Mobile WiMAX™ (IEEE 802.16e), which encompasses the earlier WiBro developed by the Telecommunications Technology Association (TTA) in Korea.

All of these standards have had similar goals in terms of improving spectral efficiency, with the widest bandwidth systems providing the highest single-user data rates. However, spectral efficiencies are achieved primarily through the use of higher-order modulation schemes and multi-antenna technologies that range from basic transmit and receive diversity to the more advanced MIMO spatial diversity.

Of these standards, EDGE evolution and HSPA+ are direct extensions of existing 3GPP technologies. Mobile WiMAX is based on the existing IEEE 802.16d standard. Only LTE is considered "new."

1.5 3GPP LTE specification documents

Release 7 of the 3GPP specifications included the study phase of LTE. This study resulted in several Technical Reports, of which 25.912 and 25.913 have been noted.

The specifications themselves for the LTE E-UTRA and E-UTRAN are contained in the 36 series of Release 8, divided into the following categories:

- 36.100 series covering radio specifications and evolved Node B (eNB) conformance testing
- 36.200 series covering layer 1 (physical layer) specifications
- 36.300 series covering layer 2 and 3 air interface signaling specifications
- 36.400 series covering network signaling specifications
- 36.500 series covering user equipment conformance testing
- 36.800 and 36.900 series, which are technical reports containing background information

The specifications for the EPC are more scattered than those for the E-UTRAN and are found in the 22-series, 23-series, 24-series, 29-series, and 33-series.

The latest versions of the LTE and SAE documents can be found at
http://www.3gpp.org/ftp/specs/latest/Rel-8/ and
http://www.3gpp.org/ftp/specs/latest/Rel-9/.

1.6 System architecture overview

Figure 2, which is taken from 23.882 [3], illustrates the complexity of legacy 2G and 3G cellular networks.

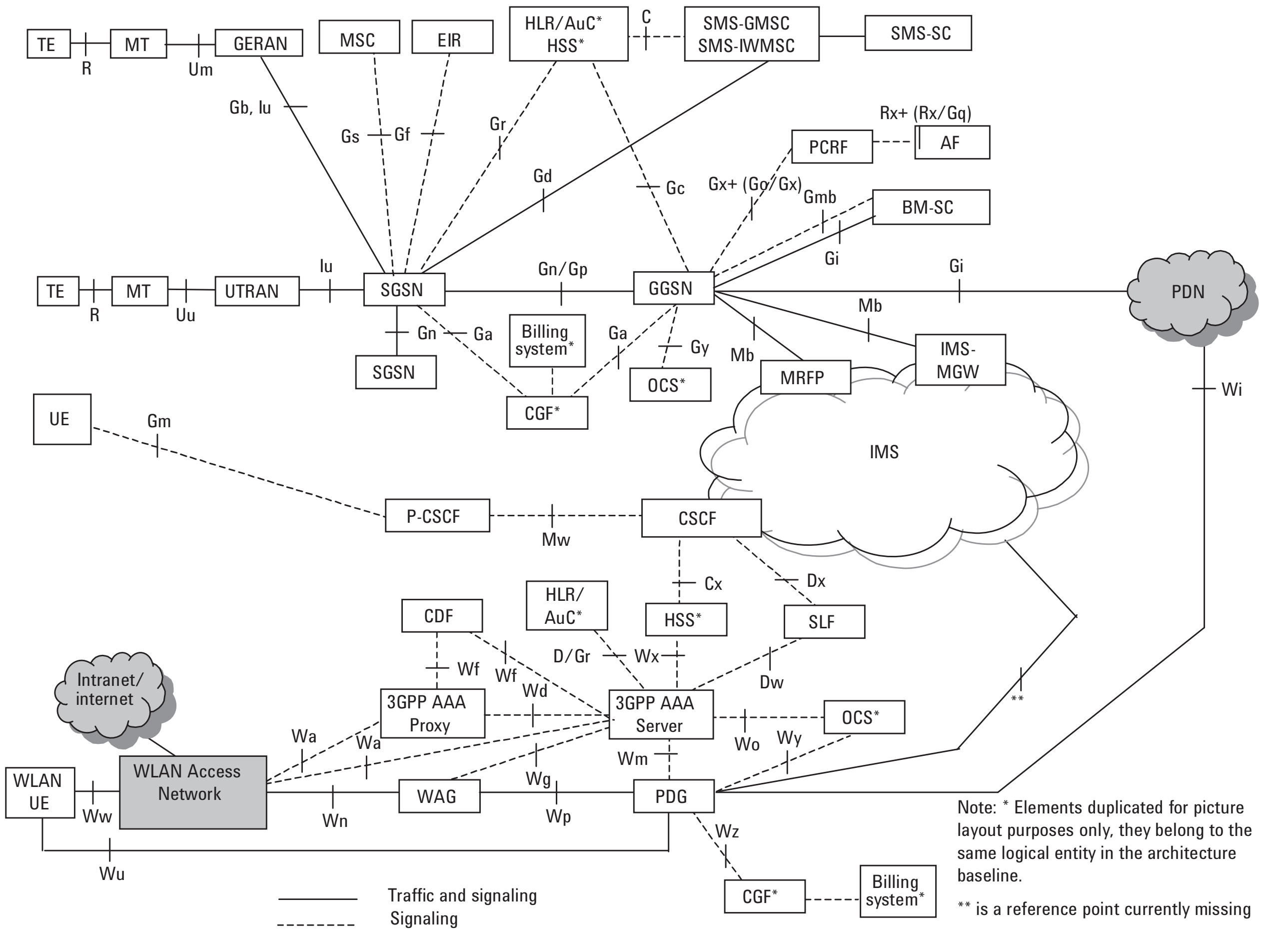

Figure 2. Logical baseline architecture for 3G (23.882 [3] Figure 4.1-1)

3GPP's drive to simplify this hybrid circuit-switched/packet-switched architecture is behind the SAE project to define an all-IP core network. This new architecture is a flatter, packet-only core network that is an essential part of delivering the higher throughput, lower cost, and lower latency that is the goal of the LTE evolved RAN. The EPC is designed also to provide seamless interworking with the existing 3GPP and non-3GPP radio access technologies.

1.6 System architecture overview (continued)

Figure 3 shows a high level view of how the LTE evolved RAN and the EPC interact with the legacy radio access technologies.

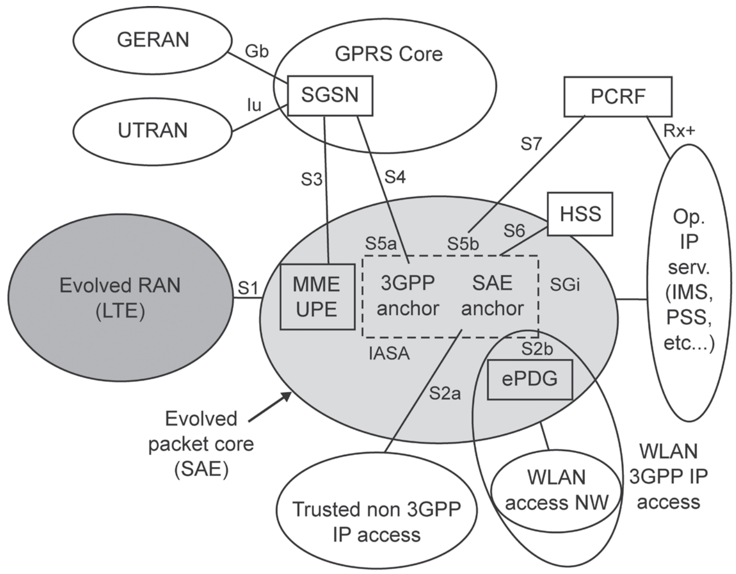

Figure 3. Logical high level architecture for the evolved system (from 23.882 [3] Figure 4.2-1)

Like the EPC, the architecture of the LTE RAN (E-UTRAN) is also greatly simplified. Figure 4, taken from 36.300 [4], shows the E-UTRAN, which contains a new network element—the eNB—that provides the E-UTRA user plane (PDCP/RLC/MAC/PHY) and control plane protocol terminations toward the UE. An eNB can serve one or more E-UTRAN cells, and it can support FDD mode, TDD mode, or FDD/TDD dual-mode operation.

1.6 System architecture overview (continued)

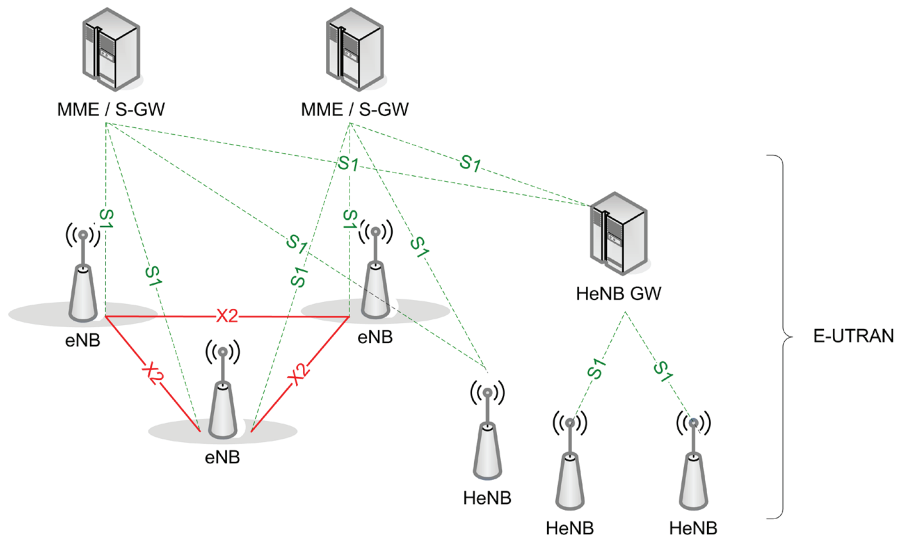

Figure 4. Overall E-UTRAN architecture with deployed HeNB gateway (36.300 [4] Figure 4.1.6-2)

A new interface in LTE called the X2 connects the eNBs as a mesh network, enabling direct communication between these elements and eliminating the need to funnel data back and forth through a radio network controller (RNC).

The S1 interface connects the E-UTRAN to the EPC, specifically by connecting the eNBs to the mobility management entity (MME) and serving gateway (S-GW) elements through a "many-to-many" relationship.

Notice that the E-UTRAN may contain Home eNBs (HeNBs), which can be connected to the EPC either directly or via an HeNB gateway (HeNB GW), as shown in Figure 4. HeNBs, or femtocells, are low power base stations that can be deployed in residential, enterprise, metropoliitan, and residential areas to provide or enhance network coverage, performance, and throughput. They may also be used to offload traffic from macrocells. 3GPP Release 8 introduced the first specifications for UMTS Home Node B (HNB) and LTE HeNB functionality. Release 9 introduced additional functionality for the HeNB to improve its operation and enhance the user experience.

In the E-UTRAN, the HeNB GW provides support for a large number of HeNBs, serving primarily as an S1-MME concentrator to the HeNBs. The HeNB GW appears to the MME as an eNB, and to the HeNB as an MME.

The S1 interface between the HeNB and the EPC is the same, whether the HeNB is connected to the EPC via an HeNB GW or not.

1.6 System architecture overview (continued)

Figure 5 from 36.300 [4] shows the functional split between the E-UTRAN and the EPC in the EPS. Yellow boxes depict the logical nodes, white boxes the functional entities of the control plane, and blue boxes the radio protocol layers.

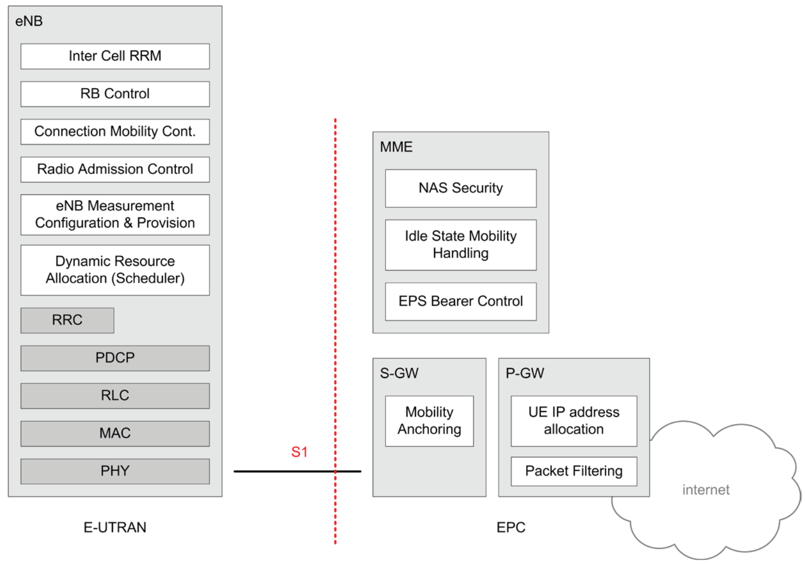

Figure 5. Functional split between E-UTRAN and EPC (36.300 [4] Figure 4.1-1)

Specifically, the eNB hosts these functions:

- Radio resource management
- IP header compression and encryption
- Selection of MME at UE attachment
- Routing of user plane data towards S-GW
- Scheduling and transmission of paging messages and broadcast information
- Measurement and measurement reporting configuration for mobility and scheduling

The MME hosts many functions including:

- Non-access stratum (NAS) signaling and NAS signaling security
- Idle state mobility handling
- EPS bearer control

The S-GW provides these functions:

- Mobility anchor point for inter eNB handovers
- Termination of user-plane packets for paging reasons
- Switching of user plane for UE mobility

The packet data network gateway (P-GW) functions include:

- UE IP address allocation
- Per-user-based packet filtering
- Lawful interception

More complete listings of the functions hosted by these network elements are found in 23.401 [5].

2. LTE Air Interface Radio Aspects

The LTE radio transmission and reception specifications are documented in 36.101 [6] for the UE and 36.104 [7] for the eNB (base station).

2.1 Radio access modes

The LTE air interface supports both FDD and time division duplex (TDD) modes, each of which has its own frame structure. Previously in UMTS, which also supported FDD and TDD, the RF specifications for the UE FDD, UE TDD, base station FDD, and base station TDD modes were covered in separate documents. However, the early decision by 3GPP to fully integrate FDD and TDD modes for LTE has resulted in only one RF specification document each for the UE and base station. With the higher level of integration between the two modes, the effort required to support them should be less than it was in the past.

The LTE air interface also supports the multimedia broadcast and multicast service (MBMS), a relatively new technology for broadcasting content such as digital TV to UE using point-to-multi-point connections. The 3GPP specifications for MBMS first appeared for UMTS in Release 6. LTE specifies a more advanced MBMS service that operates over a multicast/broadcast over single-frequency network (MBSFN) using a time-synchronized common waveform that can be transmitted from multiple cells for a given duration. The MBSFN allows over-the-air combining of multi-cell transmissions in the UE, using the cyclic prefix (CP) to cover the difference in the propagation delays. To the UE, the transmissions appear to come from a single large cell. This technique makes LTE highly efficient for MBMS transmission. The MBMS service is defined in Release 9 of the 3GPP specifications and enhanced in Release 11.

2.2 Transmission bandwidths

LTE must support the international wireless market and regional spectrum regulations and spectrum availability. To this end the specifications include variable channel bandwidths selectable from 1.4 to 20 MHz, with subcarrier spacing of 15 kHz. Subcarrier spacing is constant regardless of the channel bandwidth. 3GPP has defined the LTE air interface to be “bandwidth agnostic,” which allows the air interface to adapt to different channel bandwidths with minimal impact on system operation.

The smallest amount of resource that can be allocated in the uplink or downlink is called a resource block (RB). The transmission bandwidth configuration is defined in RBs and represents the maximum number of RBs that can be transmitted for any channel bandwidth, as given in Table 3.

Table 3. Transmission bandwidth configuration (based on 36.101 [6] Table 5.6-1)

Channel bandwidth (MHz)	**1.4**	**3**	**5**	**10**	**15**	**20**
Transmission bandwidth configuration (N_{RB})	6	15	25	50	75	100

2.3 Supported frequency bands

The LTE specifications inherit all the frequency bands defined for UMTS, which is a list that continues to grow.

Table 4. E-UTRA operating bands (TS 36.101 [6] Table 5.5-1)

E-UTRA operating band	**Uplink (UL) operating band BS receive UE transmit** **FUL_low – FUL_high**	**Downlink (DL) operating band BS transmit UE receive** **FDL_low – FDL_high**	**Duplex mode**
1	1920 – 1980 MHz	2110 – 2170 MHz	FDD
2	1850 – 1910 MHz	1930 – 1990 MHz	FDD
3	1710 – 1785 MHz	1805 – 1880 MHz	FDD
4	1710 – 1755 MHz	2110 – 2155 MHz	FDD
5	824 – 849 MHz	869 – 894 MHz	FDD
6	830 – 840 MHz	875 – 885 MHz	FDD
7	2500 – 2570 MHz	2620 – 2690 MHz	FDD
8	880 – 915 MHz	925 – 960 MHz	FDD
9	1749.9 – 1784.9 MHz	1844.9 – 1879.9 MHz	FDD
10	1710 – 1770 MHz	2110 – 2170 MHz	FDD
11	1427.9 – 1452.9 MHz	1475.9 – 1500.9 MHz	FDD
12	698 – 716 MHz	728 – 746 MHz	FDD
13	777 – 787 MHz	746 – 756 MHz	FDD
14	788 – 798 MHz	758 – 768 MHz	FDD
15	Reserved	Reserved	FDD
16	Reserved	Reserved	FDD
17	704 MHz – 716 MHz	734 MHz – 746 MHz	FDD
18	815 MHz – 830 MHz	860 MHz – 875 MHz	FDD
19	830 MHz – 845 MHz	875 MHz – 890 MHz	FDD
20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
21	1447.9 MHz – 1462.9 MHz	1495.9 MHz – 1510.9 MHz	FDD
...			
33	1900 – 1920 MHz	1900 – 1920 MHz	TDD
34	2010 – 2025 MHz	2010 – 2025 MHz	TDD
35	1850 – 1910 MHz	1850 – 1910 MHz	TDD
36	1930 – 1990 MHz	1930 – 1990 MHz	TDD
37	1910 – 1930 MHz	1910 – 1930 MHz	TDD
38	2570 – 2620 MHz	2570 – 2620 MHz	TDD
39	1880 – 1920 MHz	1880 – 1920 MHz	TDD
40	2300 – 2400 MHz	2300 – 2400 MHz	TDD

2.4 Peak single user data rates and UE capabilities

The estimated peak data rates deemed feasible for the LTE system in ideal conditions are very high, and range from 100 to 326.4 Mbps on the downlink and 50 to 86.4 Mbps and higher on the uplink depending on the antenna configuration and modulation depth. These rates represent the corner case of what can be achieved with the LTE RAN in perfect radio conditions; however, it is necessary for practical reasons to introduce lower levels of performance to enable a range of implementation choices for system deployment. This is achieved through the introduction of UE categories as specified in 36.306 [8] and shown in Table 5. These are similar in concept to the categories used to specify different levels of performance for HSPA.

Table 5. Peak data rates for UE categories (derived from 36.306 [8] Tables 4.1-1 and 4.1-2)

UE category	Peak downlink data rate (Mbps)	Downlink antenna configuration (eNB transmit x UE receive)	Peak uplink data rate (Mbps)	Support for 64QAM in uplink
Category 1	10.296	1 x 2	5.16	No
Category 2	51.024	2 x 2	25.456	No
Category 3	102.048	2 x 2	51.024	No
Category 4	150.752	2 x 2	51.024	No
Category 5	299.552	4 x 2	75.376	Yes

Note that the UE category for the downlink and for the uplink must be the same.

2.5 Multi-standard radio

Release 9 introduced the concept of multi-standard radio (MSR). This was in recognition of the evolution of base station technology, which enabled more than one carrier from the same or another radio access technology to be operated from a single base station using a wideband transceiver. The introduction of MSR has not resulted in new radio requirements as such but it has changed the way in which the existing radio requirements for LTE and other systems such as UMTS and GSM are interpreted for the purposes of conformance testing. New technical specification 37.141 covers MSR conformance testing.

2.6 Multiple access technology in the downlink: OFDM and OFDMA

Downlink and uplink transmission in LTE are based on the use of multiple access technologies: specifically, orthogonal frequency division multiple access (OFDMA) for the downlink, and single-carrier frequency division multiple access (SC-FDMA) for the uplink.

The downlink is considered first. OFDMA is a variant of orthogonal frequency division multiplexing (OFDM), a digital multi-carrier modulation scheme that is widely used in wireless systems but relatively new to cellular. Rather than transmit a high-rate stream of data with a single carrier, OFDM makes use of a large number of closely spaced orthogonal subcarriers that are transmitted in parallel. Each subcarrier is modulated with a conventional modulation scheme (such as QPSK, 16QAM, or 64QAM) at a low symbol rate. The combination of hundreds or thousands of subcarriers enables data rates similar to conventional single-carrier modulation schemes in the same bandwidth.

The diagram in Figure 6 taken from 25.892 [9] illustrates the key features of an OFDM signal in frequency and time. In the frequency domain, multiple adjacent tones or subcarriers are each independently modulated with data. Then in the time domain, guard intervals are inserted between each of the symbols to prevent inter-symbol interference at the receiver caused by multi-path delay spread in the radio channel.

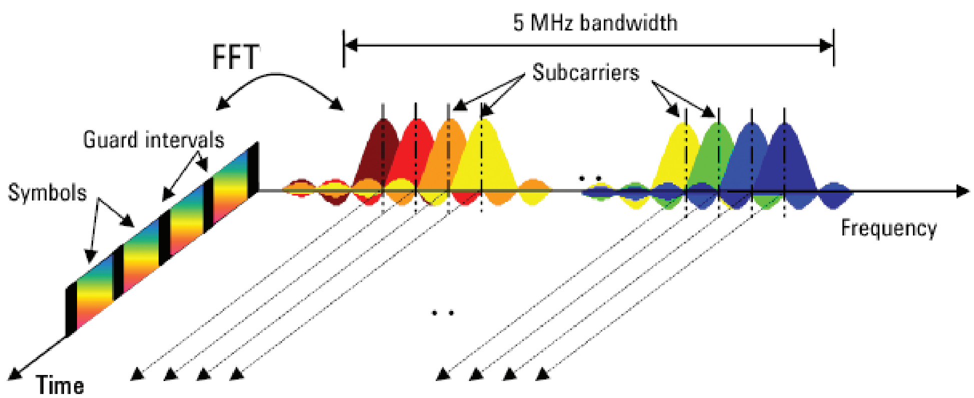

Figure 6. OFDM signal represented in frequency and time (25.892 [9] Figure 1)

Although OFDM has been used for many years in communication systems, its use in mobile devices is more recent. The European Telecommunications Standards Institute (ETSI) first looked at OFDM for GSM back in the late 1980s; however, the processing power required to perform the many FFT operations at the heart of OFDM was at that time too expensive and demanding for a mobile application. In 1998, 3GPP seriously considered OFDM for UMTS, but again chose an alternative technology based on code division multiple access (CDMA). Today the cost of digital signal processing has been greatly reduced and OFDM is now considered a commercially viable method of wireless transmission for the handset.

2.6 Multiple access technology in the downlink: OFDM and OFDMA (continued)

When compared to the CDMA technology upon which UMTS is based, OFDM offers a number of distinct advantages:

- OFDM can easily be scaled up to wide channels that are more resistant to fading.
- OFDM channel equalizers are much simpler to implement than are CDMA equalizers, as the OFDM signal is represented in the frequency domain rather than the time domain.
- OFDM can be made completely resistant to multi-path delay spread. This is possible because the long symbols used for OFDM can be separated by a guard interval known as the cyclic prefix (CP). The CP is a copy of the end of a symbol inserted at the beginning. By sampling the received signal at the optimum time, the receiver can remove the time domain interference between adjacent symbols caused by multi-path delay spread in the radio channel.
- OFDM is better suited to MIMO. The frequency domain representation of the signal enables easy precoding to match the signal to the frequency and phase characteristics of the multi-path radio channel.

However, OFDM does have some disadvantages. The subcarriers are closely spaced making OFDM sensitive to frequency errors and phase noise. For the same reason, OFDM is also sensitive to Doppler shift, which causes interference between the subcarriers. Pure OFDM also creates high peak-to-average signals, and that is why a modification of the technology called SC-FDMA is used in the uplink. SC-FDMA is discussed later.

It is known that OFDM will be more difficult to operate than CDMA at the edge of cells. CDMA uses scrambling codes to provide protection from inter-cell interference at the cell edge whereas OFDM has no such feature. Therefore, some form of frequency planning at the cell edges will be required. Figure 7 gives one example of how this might be done. The color yellow represents the entire channel bandwidth and the other colors show a plan for frequency re-use to avoid inter-cell interference at the cell edges.

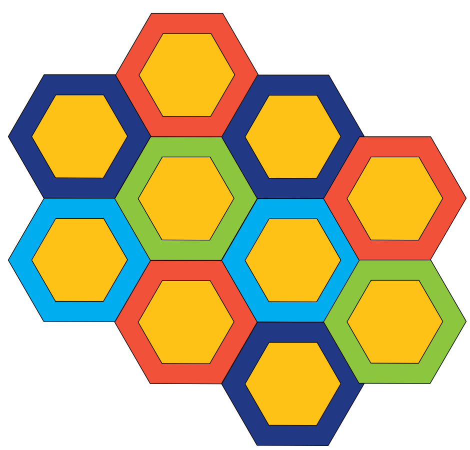

Figure 7. Example of frequency planning to avoid inter-cell interference at the cell edges

2.6 Multiple access technology in the downlink: OFDM and OFDMA (continued)

The main differences between CDMA and OFDM are summarized in Table 6.

Table 6. Comparison of CDMA and OFDM

Attribute	CDMA	OFDM
Transmission bandwidth	Full system bandwidth	Variable up to full system bandwidth
Frequency-selective scheduling	Not possible	A key advantage of OFDM although it requires accurate real-time feedback of channel conditions from receiver to transmitter
Symbol period	Very short–inverse of the system bandwidth	Very long–defined by subcarrier spacing and independent of system bandwidth
Equalization	Difficult above 5 MHz	Easy for any bandwidth due to signal representation in the frequency domain
Resistance to multipath	Difficult above 5 MHz	Completely free of multipath distortion up to the CP length
Suitability for MIMO	Requires significant computing power due to signal being defined in the time domain	Ideal for MIMO due to signal representation in the frequency domain and possibility of narrowband allocation to follow real-time variations in the channel
Sensitivity to frequency domain distortion and interference	Averaged across the channel by the spreading process	Vulnerable to narrow-band distortion and interference
Separation of users	Scrambling and orthogonal spreading codes	Frequency and time although scrambling and spreading can be added as well

With standard OFDM, very narrow UE-specific transmissions can suffer from narrowband fading and interference. That is why for the downlink 3GPP chose OFDMA, which incorporates elements of time division multiple access (TDMA). OFDMA allows subsets of the subcarriers to be allocated dynamically among the different users on the channel, as shown in Figure 8. The result is a more robust system with increased capacity. This is due to the trunking efficiency of multiplexing low rate users and the ability to schedule users by frequency, which provides resistance to frequency-selective fading.

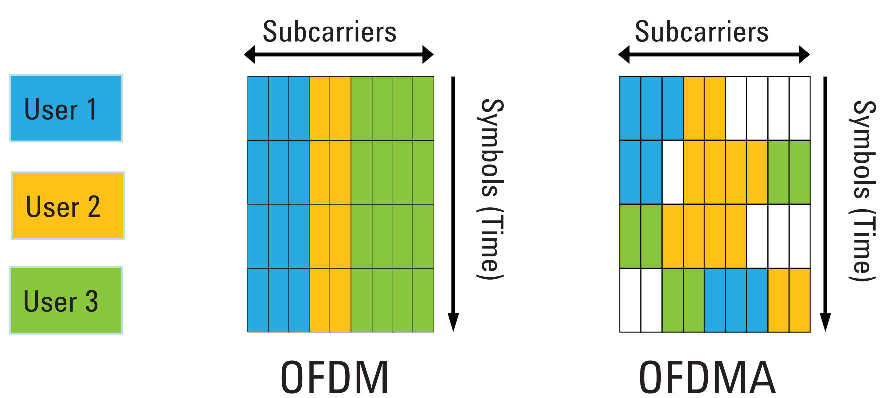

Figure 8. OFDM and OFDMA subcarrier allocation

2.7 Multiple access technology in the uplink: SC-FDMA

The high peak-to-average ratio (PAR) associated with OFDM led 3GPP to look for a different transmission scheme for the LTE uplink. SC-FDMA was chosen because it combines the low PAR techniques of single-carrier transmission systems, such as GSM and CDMA, with the multi-path resistance and flexible frequency allocation of OFDMA.

A mathematical description of an SC-FDMA symbol in the time domain is given in 36.211 [10] sub-clause 5.6. A brief description is as follows: data symbols in the time domain are converted to the frequency domain using a discrete Fourier transform (DFT); then in the frequency domain they are mapped to the desired location in the overall channel bandwidth before being converted back to the time domain using an inverse FFT (IFFT). Finally, the CP is inserted. Because SC-FDMA uses this technique, it is sometimes called discrete Fourier transform spread OFDM or (DFT-SOFDM), although this terminology is becoming less common. SC-FDMA is explained in more detail below.

2.7.1 OFDMA and SC-FDMA compared

A graphical comparison of OFDMA and SC-FDMA as shown in Figure 9 is helpful in understanding the differences between these two modulation schemes. For clarity this example uses only four (M) subcarriers over two symbol periods with the payload data represented by quadrature phase shift keying (QPSK) modulation. As described earlier, real LTE signals are allocated in units of 12 adjacent subcarriers.

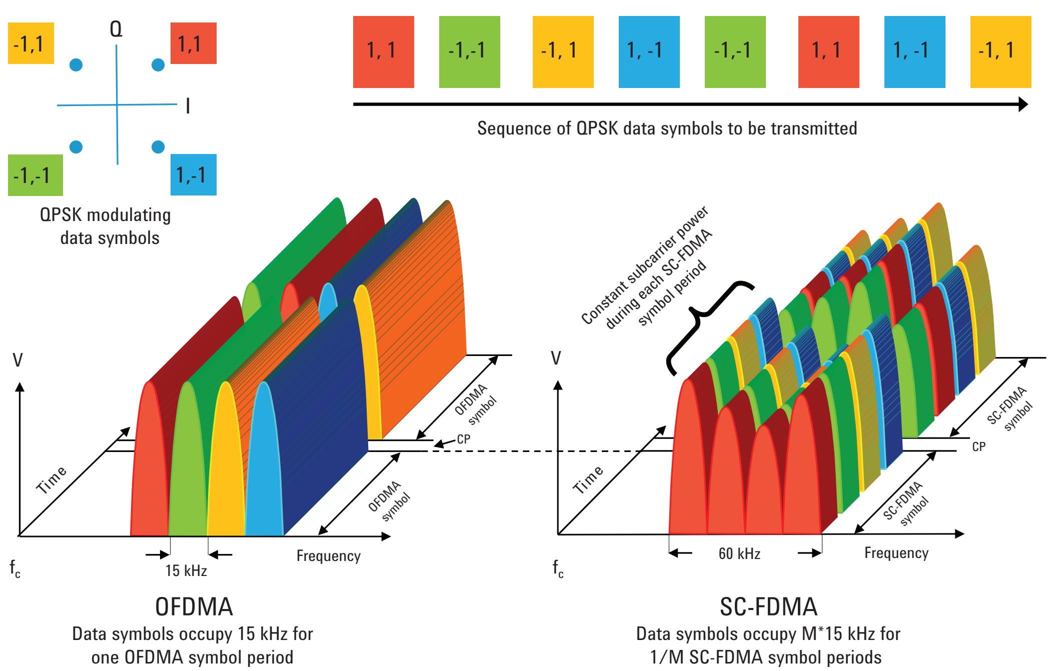

Figure 9. Comparison of OFDMA and SC-FDMA transmitting a series of QPSK data symbols

2.7.1 OFDMA and SC-FDMA compared (continued)

On the left side of Figure 9, M adjacent 15 kHz subcarriers—already positioned at the desired place in the channel bandwidth—are each modulated for the OFDMA symbol period of 66.7 µs by one QPSK data symbol. In this four subcarrier example, four symbols are taken in parallel. These are QPSK data symbols so only the phase of each subcarrier is modulated and the subcarrier power remains constant between symbols. After one OFDMA symbol period has elapsed, the CP is inserted and the next four symbols are transmitted in parallel. For visual clarity, the CP is shown as a gap; however, it is actually filled with a copy of the end of the next symbol, which means that the transmission power is continuous but has a phase discontinuity at the symbol boundary. To create the transmitted signal, an IFFT is performed on each subcarrier to create M time-domain signals. These in turn are vector-summed to create the final time-domain waveform used for transmission.

SC-FDMA signal generation begins with a special precoding process but then continues in a manner similar to OFDMA. Before getting into the details of the generation process it is helpful to describe the end result as shown on the right side of Figure 9. The most obvious difference between the two schemes is that OFDMA transmits the four QPSK data symbols in parallel, one per subcarrier, while SC-FDMA transmits the four QPSK data symbols in series at four times the rate, with each data symbol occupying M x 15 kHz bandwidth.

Visually, the OFDMA signal is clearly multi-carrier with one data symbol per subcarrier, but the SC-FDMA signal appears to be more like a single-carrier (hence the “SC” in the SC-FDMA name) with each data symbol being represented by one wide signal. Note that OFDMA and SC-FDMA symbol lengths are the same at 66.7 µs; however, the SC-FDMA symbol contains M “sub-symbols” that represent the modulating data. It is the parallel transmission of multiple symbols that creates the undesirable high PAR of OFDMA. By transmitting the M data symbols in series at M times the rate, the SC-FDMA occupied bandwidth is the same as multi-carrier OFDMA but, crucially, the PAR is the same as that used for the original data symbols. Adding together many narrow-band QPSK waveforms in OFDMA will always create higher peaks than would be seen in the wider-bandwidth, single-carrier QPSK waveform of SC-FDMA. As the number of subcarriers M increases, the PAR of OFDMA with random modulating data approaches Gaussian noise statistics but, regardless of the value of M, the SC-FDMA PAR remains the same as that used for the original data symbols.

2.7.2 SC-FDMA signal generation

As noted, SC-FDMA signal generation begins with a special precoding process. Figure 10 shows the first steps, which create a time-domain waveform of the QPSK data sub-symbols. Using the four color-coded QPSK data symbols from Figure 9, the process creates one SC-FDMA symbol in the time domain by computing the trajectory traced by moving from one QPSK data symbol to the next. This is done at M times the rate of the SC-FDMA symbol such that one SC-FDMA symbol contains M consecutive QPSK data symbols. Time-domain filtering of the data symbol transitions occurs in any real implementation, although it is not discussed here.

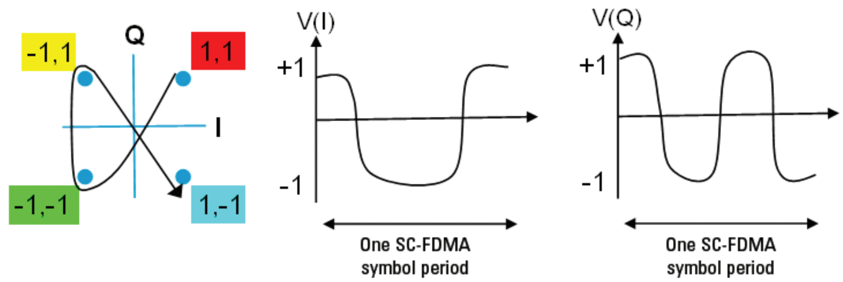

Figure 10. Creating the time-domain waveform of an SC-FDMA symbol

Once an IQ representation of one SC-FDMA symbol has been created in the time domain, the next step is to represent that symbol in the frequency domain using a DFT. This is shown in Figure 11. The DFT sampling frequency is chosen such that the time-domain waveform of one SC-FDMA symbol is fully represented by M DFT bins spaced 15 kHz apart, with each bin representing one subcarrier in which amplitude and phase are held constant for 66.7 µs.

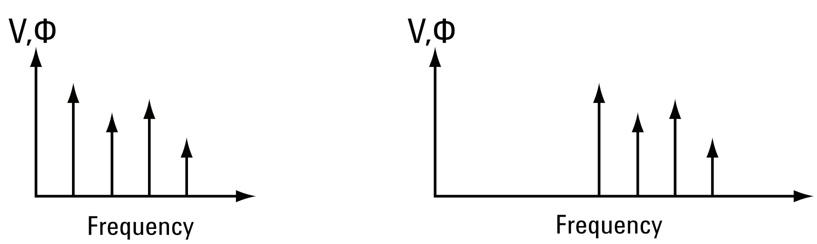

Figure 11. Baseband and frequency shifted DFT representations of an SC-FDMA symbol

A one-to-one correlation always exists between the number of data symbols to be transmitted during one SC-FDMA symbol period and the number of DFT bins created. This in turn becomes the number of occupied subcarriers. When an increasing number of data symbols are transmitted during one SC-FDMA period, the time-domain waveform changes faster, generating a higher bandwidth and hence requiring more DFT bins to fully represent the signal in the frequency domain. Note in Figure 11 that there is no longer a direct relationship between the amplitude and phase of the individual DFT bins and the original QPSK data symbols. This differs from the OFDMA example in which data symbols directly modulate the subcarriers.

2.7.2 SC-FDMA signal generation (continued)

The next step of the signal generation process is to shift the baseband DFT representation of the time-domain SC-FDMA symbol to the desired part of the overall channel bandwidth. Because the signal is now represented as a DFT, frequency-shifting is a simple process achieved by copying the M bins into a larger DFT space of N bins. This larger space equals the size of the system channel bandwidth, of which there are six to choose from in LTE spanning 1.4 to 20 MHz. The signal can be positioned anywhere in the channel bandwidth, thus executing the frequency-division multiple access (FDMA) essential for efficiently sharing the uplink between multiple users.

To complete SC-FDMA signal generation, the process follows the same steps as for OFDMA. Performing an IDFT converts the frequency-shifted signal to the time domain and inserting the CP provides the fundamental robustness of OFDMA against multipath. The relationship between SC-FDMA and OFDMA is illustrated in Figure 12.

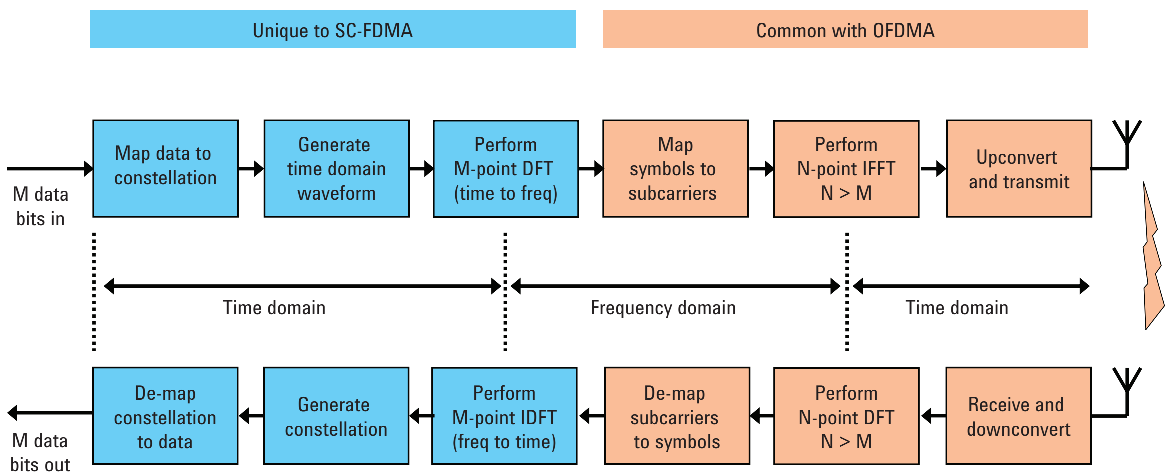

Figure 12. Simplified model of SC-FDMA and OFDMA signal generation and reception

2.7.2 SC-FDMA signal generation (continued)

At this point, it is reasonable to ask how SC-FDMA can be resistant to multipath when the data symbols are still short. In OFDMA, the modulating data symbols are constant over the 66.7 µs OFDMA symbol period, but an SC-FDMA symbol is not constant over time since it contains M sub-symbols of much shorter duration. The multipath resistance of the OFDMA demodulation process seems to rely on the long data symbols that map directly onto the subcarriers. Fortunately, it is the constant nature of each subcarrier—not the data symbols—that provides the resistance to delay spread. As shown in Figure 9 and Figure 11, the DFT of the time-varying SC-FDMA symbol generated a set of DFT bins constant in time during the SC-FDMA symbol period, even though the modulating data symbols varied over the same period. It is inherent to the DFT process that the time-varying SC-FDMA symbol, made of M serial data symbols, is represented in the frequency domain by M time-invariant subcarriers. Thus, even SC-FDMA with its short data symbols benefits from multipath protection.

It may seem counter intuitive that M time-invariant DFT bins can fully represent a time-varying signal. However, the DFT principle is simply illustrated by considering the sum of two fixed sine waves at different frequencies. The result is a non-sinusoidal time-varying signal, fully represented by two fixed sine waves.

Table 7 summarizes the differences between the OFDMA and SC-FDMA modulation schemes. When OFDMA is analyzed one subcarrier at a time, it resembles the original data symbols. At full bandwidth, however, the signal looks like Gaussian noise in terms of its PAR statistics and the constellation. The opposite is true for SC-FDMA. In this case, the relationship to the original data symbols is evident when the entire signal bandwidth is analyzed. The constellation (and hence low PAR) of the original data symbols can be observed rotating at M times the SC-FDMA symbol rate, ignoring the seven percent rate reduction that is due to adding the CP. When analyzed at the 15 kHz subcarrier spacing, the SC-FDMA PAR and constellation are meaningless because they are M times narrower than the information bandwidth of the data symbols.

Table 7. Analysis of OFDMA and SC-FDMA at different bandwidths

Modulation format	**OFDMA**		**SC-FDMA**	
Analysis bandwidth	**15 kHz**	**Signal bandwidth (M * 15 kHz)**	**15 kHz**	**Signal bandwidth (M * 15 kHz)**
Peak-to-average power ratio	Same as data symbol	High PAPR (Gaussian)	Lower than data symbol (not meaningful)	Same as data symbol
Observable IQ constellation	Same as data symbol at 1/66.7 µs rate	Not meaningful (Gaussian)	Not meaningful (Gaussian)	Same as data symbol at M/66.7 µs rate

2.7.3 Examining an SC-FDMA signal

Unlike the eNB, the UE does not normally transmit across the entire channel bandwidth. A typical uplink configuration with the definition of terms is shown in Figure 13.

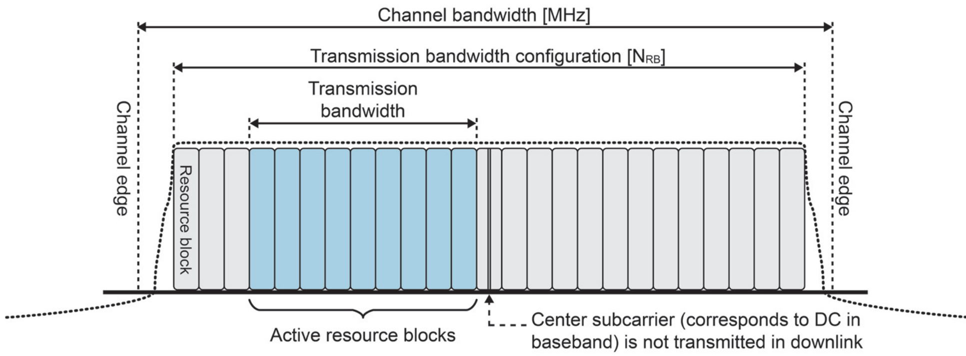

Figure 13. Definition of channel bandwidth and transmission bandwidth configuration for one E-UTRA carrier (36.101 [6] Figure 5.6-1)

Figure 14 shows some of the measurements that can be made on a typical SC-FDMA signal where the allocated transmission bandwidth is less than the transmission bandwidth configuration. Six different views or traces are shown. The constellation in trace A (top left) shows that the signal of interest is a 16QAM signal. The unity circle represents the reference signals (RS) occurring every seventh symbol, which do not use SC-FDMA but are phase-modulated using an orthogonal Zadoff-Chu sequence.

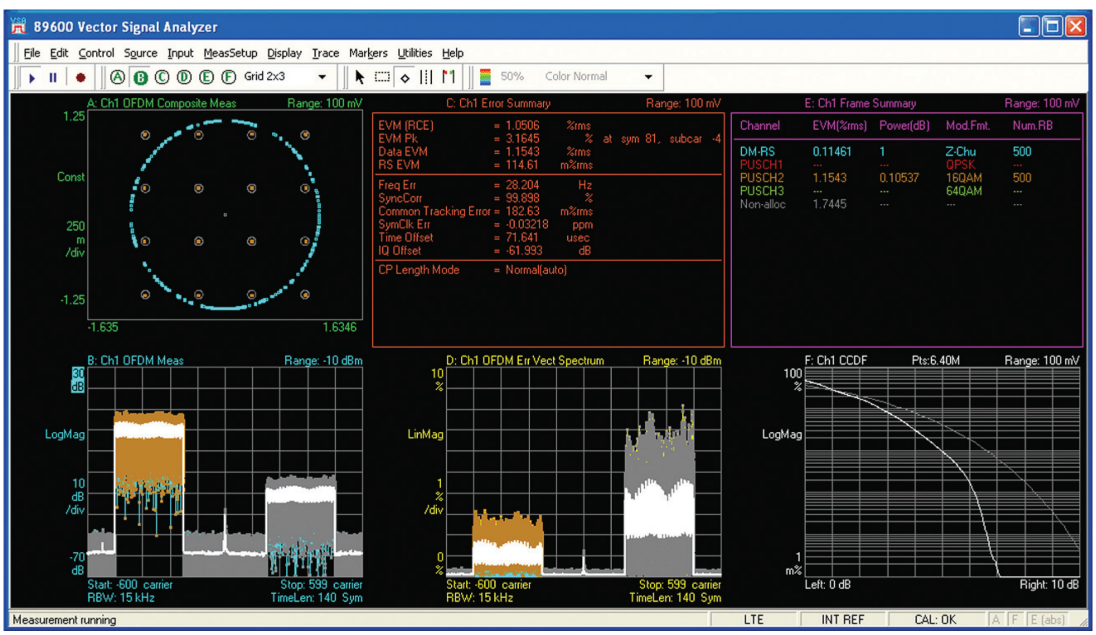

Figure 14. Analysis of a 16QAM SC-FDMA signal

2.7.3 Examining an SC-FDMA signal (continued)

Trace B (lower left) shows signal power versus frequency. The frequency scale is in 15 kHz subcarriers numbered from –600 to 599, which represents a transmission bandwidth configuration of 18 MHz or 100 RB. The channel bandwidth is therefore 20 MHz and the allocated transmission bandwidth is 5 MHz towards the lower end. The brown dots represent the instantaneous subcarrier amplitude and the white dots the average over 10 ms. In the center of the trace, the spike represents the local oscillator (LO) leakage—IQ offset—of the signal; the large image to the right is an OFDM artifact deliberately created using 0.5 dB IQ gain imbalance in the signal. Both the LO leakage and the power in non-allocated subcarriers are limited by the 3GPP specifications.

Trace C (top middle) shows a summary of the measured impairments including the error vector magnitude (EVM), frequency error, and IQ offset. Note the data EVM at 1.15 percent is much higher than the RS EVM at 0.114 percent. This is due to a +0.1 dB boost in the data power as reported in trace E, which for this example was ignored by the receiver to create data-specific EVM. Also note that the reference signal (RS) power boost is reported as +1 dB, which can be observed in the IQ constellation of Trace A because the unity circle does not pass through eight of the 16QAM points. Trace D (lower middle) shows the distribution of EVM by subcarrier. The average and peak of the allocated signal EVM is in line with the numbers in trace C. The EVM for the non-allocated subcarriers reads much higher, although the size of this impairment is specified with a new, "in-band emission" requirement as a power ratio between the allocated RB and unallocated RB. The ratio for this particular signal is around 30 dB as trace B shows. The blue dots (along the X axis) in trace D also show the EVM of the RS, which is very low.

Trace E (top right) shows a measurement of EVM versus modulation type from one capture. This signal uses only the RS phase modulation and 16QAM so the QPSK and 64QAM results are blank. Finally, trace F (lower right) shows the PAR—the whole point of SC-FDMA—in the form of a complementary cumulative distribution function (CCDF) measurement. It is not possible to come up with a single figure of merit for the PAR advantage of SC-FDMA over OFDMA because it depends on the data rate. The PAR of OFDMA is always higher than SC-FDMA even for narrow frequency allocations; however, when data rates rise and the frequency allocation gets wider, the SC-FDMA PAR remains constant but OFDMA gets worse and approaches Gaussian noise. A 5 MHz OFDMA 16QAM signal would look very much like Gaussian noise. From the lower white trace it can be seen at 0.01 percent probability that the SC-FDMA signal is 3 dB better than the upper blue Gaussian reference trace. As every amplifier designer knows, shaving even a tenth of a decibel from the peak power budget is a significant improvement.

2.8 Overview of multiple antenna techniques

Central to LTE is the concept of multiple antenna techniques, which are used to increase coverage and physical layer capacity. Adding more antennas to a radio system gives the possibility of performance improvements because the radiated signals will take different physical paths and undergo variations in polarization. There are three kinds of multi-antenna applications. The first makes direct use of path diversity in which one radiated path may be subject to fading loss and another may not. Diversity can be introduced at the transmitter, the receiver, or both simultaneously. The second applies beamsteering by controlling the phase relationship of the electrical signals radiated at the antennas to direct transmitted energy toward the physical location of the UE. The third uses the path diversity—introduced by separating the antennas in space or by polarization—to enable spatial multiplexing. Spatial multiplexing allows for the simultaneous transmission of more than one stream of data in the same time and frequency. The term multiple input multiple output (MIMO) is typically used to describe spatial multiplexing and it is worth some explanation here to avoid potential confusion. The I and the O in MIMO refer to the channel through which the radio signal propagates and not to inputs or outputs of the devices at either end of the link.

Another term commonly associated with MIMO is beamforming. Beamforming is a more complex technique used to further enhance the transmission. Feedback is used to adapt a signal to the channel conditions. The transmitted signal can be modified either in amplitude or phase or additionally cross-coupled.

As Figure 15 shows, there are four ways to make use of the radio channel. For simplicity, the examples depicted use only one or two antennas. Notice that the terms used to label the radio channel access modes (the “I” and “O” in the acronyms) refer to the inputs and outputs of the radio channel rather than the transmitters and receivers of the devices.

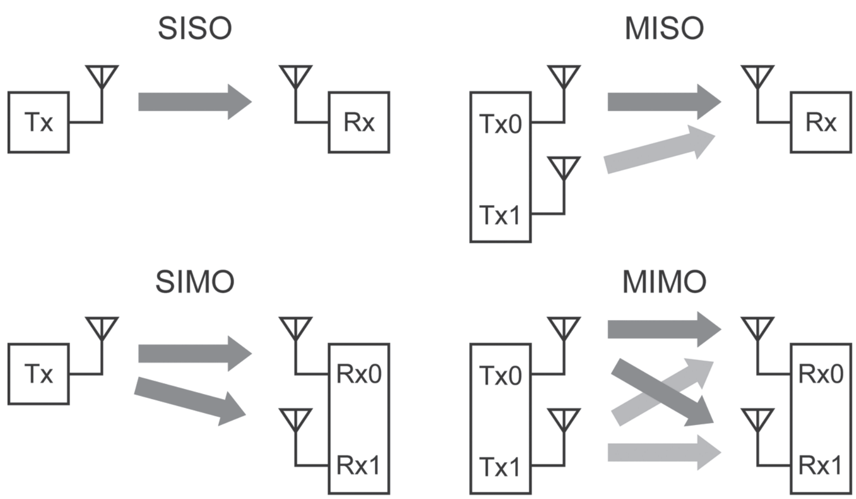

Figure 15. Radio-channel access modes

2.8.1 Single input single output

The most basic radio channel access mode is single input single output (SISO), in which only one transmit antenna and one receive antenna are used. This is the form of communications that has been the default since radio began and is the baseline against which all the multiple antenna techniques are compared.

2.8.2 Single input multiple output

A second mode shown in Figure 15 is single input multiple output (SIMO), which uses one transmitter and two or more receivers. SIMO is often referred to as receive diversity. This radio channel access mode is particularly well suited for low signal-to-noise (SNR) conditions in which a theoretical gain of 3 dB is possible when two receivers are used. There is no change in the data rate since only one data stream is transmitted, but coverage at the cell edge is improved due to the lowering of the usable SNR.

2.8.3 Multiple input single output

Multiple input single output (MISO) mode uses two or more transmitters and one receiver. (Figure 15 shows only two transmitters and one receiver for simplicity.) MISO is more commonly referred to as transmit diversity. The same data is sent on both transmitting antennas but coded such that the receiver can identify each transmitter. Transmit diversity increases the robustness of the signal to fading and can increase performance in low SNR conditions. MISO does not increase the data rates, but it supports the same data rates using less power. Transmit diversity can be enhanced with closed loop feedback from the receiver to indicate to the transmitter the optimum balance of phase and power used for each transmit antenna.

2.8.4 Multiple input multiple output

The final mode shown in Figure 15 is full MIMO, which requires two or more transmitters and two or more receivers. MIMO increases spectral capacity by transmitting multiple data streams simultaneously in the same frequency and time, taking full advantage of the different paths in the radio channel. For a system to be described as MIMO, it must have at least as many receivers as there are transmit streams.

The number of transmit streams should not be confused with the number of transmit antennas. (Streams, also called layers, here refers to the signals in the channel.) Consider the Tx diversity (MISO) case in which two transmitters are present but only one data stream. Adding receive diversity (SIMO) does not turn this configuration into MIMO, even though there are now two Tx and two Rx antennas involved. In other words, SIMO + MISO ≠ MIMO. It is always possible to have more transmitters than data streams but not the other way around. If N data streams are transmitted from fewer than N antennas, the data cannot be fully descrambled by any number of receivers since overlapping streams without the addition of spatial diversity just creates interference. However, by spatially separating N streams across at least N antennas, N receivers will be able to fully reconstruct the original data streams provided the path correlation and noise in the radio channel are low enough.

Another crucial factor for MIMO operation is that the paths must be decorrelated. That is, the transmissions from each antenna must be uniquely identifiable so that each receiver can determine what combination of transmissions has been received. If two signals show up at the receiver and they are identical, there is no benefit of MIMO.

2.8.4 Multiple input multiple output (continued)

Note that MIMO spatial multiplexing can be combined with diversity to further improve performance.

The basics of spatial multiplexing operation can be understood by using a static, four port network to represent the channel, as shown in Figure 16.

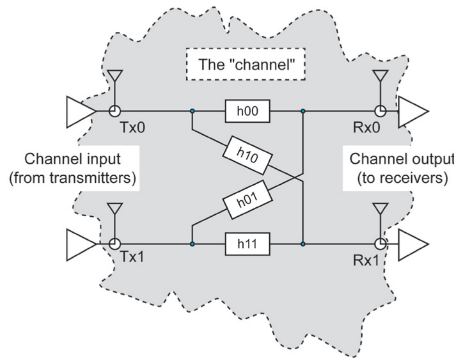

Figure 16. 2x2 MIMO, no precoding

In this figure, two signals containing different user data are simultaneously transmitted and received. Predefined training signals are transmitted from each antenna at A and B. The receiver knows which training signal was used for each antenna and therefore can calculate the channel amplitude and the phase responses h00 and h10, and h01 and h11. (Note that a convention of the channel matrix definition is to specify the receiver first.) In this way the receiver can calculate the transformation that the signals from each antenna have undergone. Since the unknown data is sent at or around the same time as the known training signal, the receiver can assume that the part of the signal containing the unknown user data from each antenna has undergone the same transformation as the known part of the signal. In essence, spatial multiplexing is using a "trick": known training signals are mixed with the randomly varying data in such a way that the unknown data can be recovered.

A key point to note about MIMO is that there must be at least as many receiving antennas as there are transmitted data streams. However, this number of streams should not be confused with the number of transmitting antennas, which may be higher than the number of streams if transmit diversity is mixed with spatial multiplexing. The minimum number of receivers is determined by what is mathematically required for the calculation of the channel matrix H. If there are fewer receivers than transmitted data streams, it is mathematically impossible to resolve the channel matrix meaning the additional transmit data streams contribute interference to the other streams rather than additional information.

This simplified description of 2 x 2 spatial multiplexing operation intentionally does not consider the source of the data. There is a lot of flexibility in how the two data streams can be used. In LTE, the source data for each stream can have different modulation and coding and does not need be associated with a single user.

It is necessary to consider how to design the training signals to suit the characteristics of the radio channel. For rapidly changing channels, and to suit the frame structure of the signal, LTE interleaves the known signal, called the reference signal (RS), throughout the frame in both frequency and time. The RS definition is different for the downlink and uplink, and the RS symbols are orthogonal on each antenna port in both frequency and time.

2.9 LTE multiple antenna schemes

Having described some basics of multiple antenna techniques, we now look at what LTE has specified, beginning with some terminology. The terms codeword, layer and precoding have been adopted specifically for LTE to refer to signals and their processing. Figure 17 shows the processing steps to which they refer. The terms are used in the following ways:

– **Codeword:** A codeword represents a channel-encoded and rate-matched user data transport block, protected by a hybrid automatic repeat request (HARQ) process before it is formatted for transmission. One or two codewords, CW0 and CW1, can be used depending on the prevailing channel conditions and transmission mode (TM). In the most common case of downlink single-user MIMO (SU-MIMO), two codewords are sent to a single UE, but in the case of downlink multiple user MIMO (MU-MIMO), each codeword is intended for one UE only.

– **Layer:** The term layer is synonymous with stream. The number of layers is denoted by the symbol ν (pronounced nu). The number of layers is always less than or equal to the number of transmit antennas. For Release 8 downlink spatial multiplexing, at least two layers must be supported with fallback to single layer when channel conditions do not favor multiple layers. Up to four layers are supported in Release 8 LTE. For Release 8 uplink spatial multiplexing only one layer per UE is allowed, but this enables two-layer MU-MIMO requiring two UEs.

– **Precoding:** Precoding modifies the layer signals before transmission, to adapt those layers to the channel propagation conditions as seen by the receiver. This process may be done for diversity, beamforming, or spatial multiplexing. As noted earlier, the MIMO channel conditions may favor one layer (data stream) over another. If the eNB is given information about the channel—e.g., information sent back from the UE—it can add complex cross-coupling to counteract the imbalance in the channel.

Figure 17 illustrates these concepts for SU-MIMO. User data from the base station (eNB) is multiplexed into codewords before being formatted for transmission. These codewords are mapped into layers or streams and then precoded with information that adapts the layers to the channel conditions. The precoded layers are sent through the channel where they are faded and mixed, and they are received by the mobile station (UE) where they are de-mapped and demultiplexed.

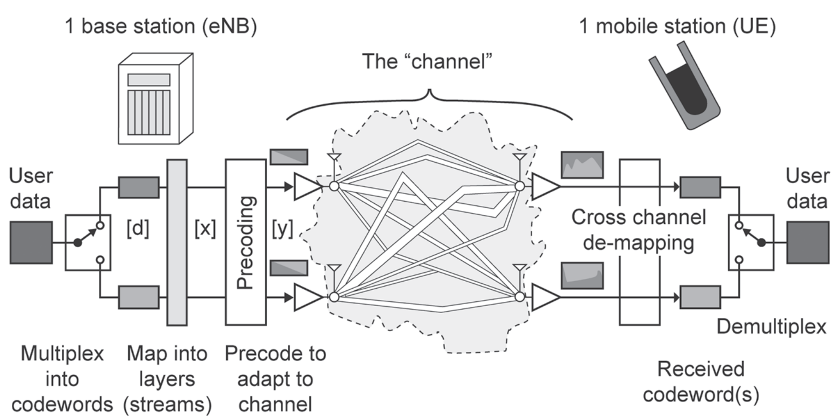

Figure 17. Signal processing for transmit diversity and spatial multiplexing (MIMO)

The symbols ***d, x,*** and ***y*** are used in the specifications to denote signals before and after layer mapping and after precoding, respectively.

2.9.1 LTE downlink multiple antenna transmission modes

Seven multiple antenna transmission modes are defined for LTE in Release 8 to optimize downlink performance under varying radio conditions. An eighth mode is added in Release 9.

Table 8. Downlink transmission modes

Transmission mode	Description	Primary benefit
1	Basic SIMO	Basic single transmit antenna operation
2	Transmit diversity	Improved signal robustness in low power/SINR conditions
3	Open-loop SU-MIMO	Potential for increased throughput in good conditions
4	Closed-loop SU-MIMO	Potential for increased throughput in good conditions
5	MU-MIMO	Improved cell spectral efficiency
6	Closed-loop Rank 1 beamsteering	Improved signal robustness
7	UE-specific RS beamforming	Improved signal robustness with non-codebook precoding
8	Dual layer UE-specific RS beamforming	As 7 with potential for increased throughput or increased cell capacity

Transmission mode 1 uses only one transmitter, and since the UE must have at least two receivers, this is a SIMO configuration, better known as receive diversity. This mode specifies the baseline receiver capability for which performance requirements will be defined. It is typically implemented using maximum ratio combining of the received streams to improve the SNR in poor conditions. Receive diversity provides little gain in good conditions.

Transmission mode 2, transmit diversity, is identical in concept to the open-loop transmit diversity introduced in UMTS Release 99. (The more complex, closed-loop transmit diversity techniques from UMTS have not been adopted in LTE, which instead uses the more advanced MIMO.) LTE supports either two or four antennas for transmit diversity. The example shown in Figure 17 is a two transmitter example in which a single stream of data is assigned to the different layers and coded using space frequency block coding (SFBC). Since this form of Tx diversity has no data rate gain, the code words CW0 and CW1 are the same. SFBC achieves robustness through frequency diversity by using different subcarriers for the repeated data on each antenna.

Transmission mode 3 is open-loop SU-MIMO in which the base station transmits two or more signals into the channel. The signals are received by a single UE, which does not send feedback; hence, no precoding is used and the data streams are mapped directly to each antenna. Open-loop transmission is used when the channel conditions are changing rapidly and there is not enough time for the coding information to be sent back and forth.

2.9.1 LTE downlink multiple antenna transmission modes (continued)

Transmission mode 4 is closed-loop SU-MIMO, which does use precoding of the layers to improve performance.

Transmission mode 5 is MU-MIMO, which is a special case of transmission mode 3. With SU-MIMO, the codewords are all intended for a single UE, which gives the potential for increased peak data rates, and the base station transmitter and UE receiver must have at least as many transmit antennas as codewords. For MU-MIMO, there can be as many codewords as there are base station transmit antennas but the destination of each codeword is toward a different UE, with each UE attempting to decode only the codeword intended for it. As a result the peak data rate per UE is not increased over basic SISO but the network has the potential for increased capacity.

Transmission mode 6, closed-loop rank 1 spatial multiplexing, is a case of transmit diversity implemented by transmitting the same signal into two antennas with phase changes applied during precoding. The precoding matrix indicator (PMI) feedback from the UE is used to select between two different transmit phases, which creates a simple binary beamsteering effect. The end result is a special case of beamforming in which the per-antenna beam weightings are limited to a fixed set of codebook-based relative phase shifts only, with constant magnitudes. The fallback mode for transmission mode 6, used when the channel conditions are changing too fast for the PMI to operate, is the traditional space-frequency block coding (SFBC) transmit diversity scheme.

Transmission mode 7 introduces the concept of UE-specific reference signals (RS). The base station transmits precoded RS, which are the training signals used in the precoding process discussed earlier. In this case the RS are transmitted for the benefit of one UE only, so they can be precoded to optimize the signal quality at the receiver. This optimal precoding allows the UE to directly decode the signals using the UE-specific RS as the reference. The downlink is thus freed from the restrictions associated with using a codebook.

Transmission mode 8, introduced in Release 9, extends the concept of UE-specific RS to support two spatial layers. These are assigned to virtual antenna ports 7 and 8. The dual-layer capability of this transmission mode also extends the potential for downlink MU-MIMO from two to four UEs. Different combinations are possible—for example, one antenna beam may support two UEs in MU-MIMO mode while the other beam supports a single UE with two layers.

2.9.2 LTE uplink multiple antenna operation

Three types of multiple antenna operation are defined for the uplink:

- Receive diversity at the eNB
- SU-MIMO for a single UE
- MU-MIMO for multiple UEs

Receive diversity was described in the previous section.

Uplink SU-MIMO is within the scope of LTE but was not fully defined until 3GPP Release 10. To implement SU-MIMO the UE requires two transmitters. This is a significant challenge in terms of cost, size, and battery consumption, and for these reasons SU-MIMO has not been a priority for development. Also, the increased data rates in the uplink that might be possible from SU-MIMO are not as important as they are in the downlink due to asymmetrical traffic distribution. Furthermore, if the system is deployed to be uplink-performance-limited, it may be impractical to increase the transmit power from the UE sufficiently to achieve the SINR needed at the eNB receivers.

Although a UE typically has a single transmitter in its baseline configuration, it nevertheless is still capable of supporting MU-MIMO. As suggested by the description of MIMO, spatial multiplexing—unlike the receive function—does not require the transmitters to be in the same physical device or location. Thus uplink MIMO can be implemented using two transmitters belonging to two different UEs. This creates the potential for an increase in uplink capacity, although an individual user will see no increase in data rates. See Figure 18.

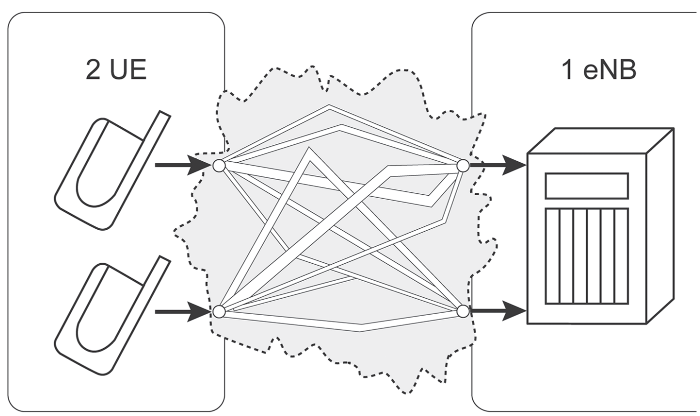

Figure 18. Multi-user MIMO in the uplink

The fact that the transmitters are physically separate has two consequences. First, there is no possibility of precoding since the source data cannot be shared between the two UEs to create the necessary cross-coupling of the data streams. This reduces the potential gains from co-located transmitters. Second, the separation of the transmitters increases the probability that the radio channels seen by the eNB will be uncorrelated. Indeed, when the eNB has to select two UEs for pairing with MU-MIMO, the primary criterion will be the presence of de-correlated channels. Any potential gains lost through lack of precoding will be more than compensated for by likely gains from better channel de-correlation. MU-MIMO therefore is a valuable technique for improving uplink capacity.

2.9.2 LTE uplink multiple antenna operation (continued)

OFDM signal recovery is tolerant of small timing and frequency errors. During normal uplink operation each UE will adjust its frequency quite precisely to that of the eNB. The eNB will also instruct the UE to adjust its timing and power so that all signals arrive at the eNB receiver at approximately the same level and time. Since the antennas are located in different devices, the transmit paths are assumed to be uncorrelated. These conditions give the eNB scheduler the opportunity to control two UEs to transmit data simultaneously using the same subcarriers.

MU-MIMO involves the simultaneous transmission of codewords via layers from different UEs at the same time and frequency. The use of normal radio management techniques will ensure adequate frequency, timing, and power alignment of the signals received at the eNB. Aligning the received power from the UEs at the eNB will be the most difficult thing to control if the potential capacity gains are to be realized.

3. LTE Air Interface Protocol Aspects

Figure 19 from 36.201 [11] shows the E-UTRA radio interface protocol architecture around the physical layer (layer 1). The physical layer provides data transport services to the higher layers. These services are accessed through transport channels via the medium access control (MAC) sub-layer. The physical layer provides transport channels to the layer 2 MAC sub-layer, and the MAC sub-layer provides logical channels to the layer 2 radio link control (RLC) sub-layer. Transport channels are characterized by how the information is transferred over the radio interface, whereas logical channels are characterized by the type of information transferred.

In the Figure 19 diagram, the circles between different layers or sub-layers indicate service access points (SAPs). Layer 1 also interfaces to the layer 3 radio resource control (RRC) layer.

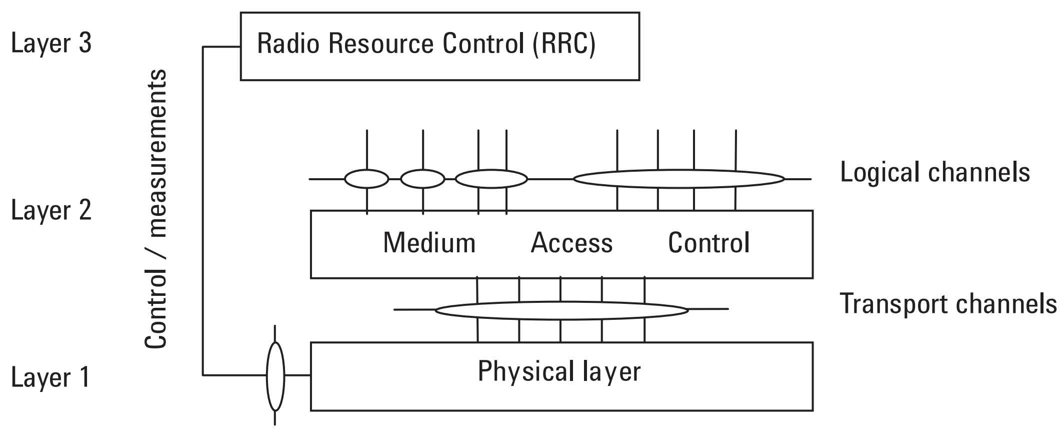

Figure 19. Radio interface protocol architecture around the physical layer (36.201 [11] Figure 1)

To enable data transport service to the higher layers, the physical layer performs a series of functions that include the following:

- Error detection on the transport channels
- Forward error correction (FEC) encoding/decoding of the transport channels
- Hybrid automatic repeat request (HARQ) soft-combining
- Rate matching and mapping of coded transport channels to physical channels
- Power weighting of physical channels
- Modulation and demodulation of physical channels
- Frequency and time synchronization
- Radio characteristics measurements and indication to higher layers
- MIMO antenna processing
- Transmit diversity
- Beamsteering
- RF processing

3.1 Physical layer overview

In addition to the overview specification (36.201), the physical layer specification is further divided among four technical specification documents as shown in Figure 20.

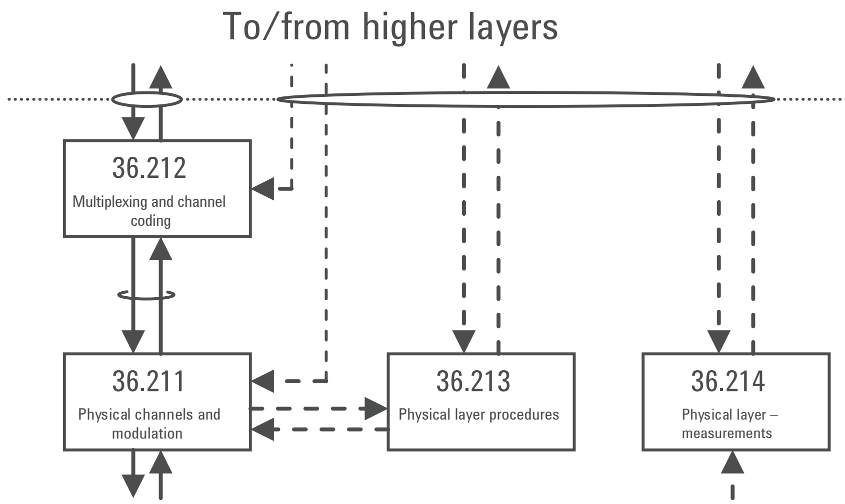

Figure 20. Relation between physical layer specifications (36.201 [11] Figure 2)

36.211 [11] Physical channels and modulation

This specification describes the uplink and downlink physical signals and physical channels, how they are modulated, and how they are mapped into the frame structure. Included is the processing for the support of multiple antenna techniques.

36.212 [12] Multiplexing and channel coding

This specification describes the transport channel and control channel data processing, including multiplexing, channel coding schemes, coding of layer 1 and Layer 2 control information, interleaving, and rate matching.

36.213 [13] Physical layer procedures

This specification describes the characteristics of the physical layer procedures including synchronization procedures, cell search and timing synchronization, power control, random access procedure, CQI reporting and MIMO feedback, UE sounding, HARQ, and ACK/NACK detection.

36.214 [14] Physical layer measurements

This specification describes the characteristics of the physical layer measurements to be performed in layer 1 by the UE and eNB, and how these measurement results are reported to higher layers and the network. This specification includes measurements for handover support.

Radio resource management

Although not strictly a part of the physical layer, the requirements for radio resource management (RRM) detailed in 36.133 [15] will be summarized since they are closely linked to the physical layer measurements.

3.2 Physical channels and modulation (36.211)

The LTE air interface consists of physical signals and physical channels, which are defined in 36.211 [10]. Physical signals are generated in layer 1 and used for system synchronization, cell identification, and radio channel estimation. Physical channels carry data from higher layers including control, scheduling, and user payload.

Physical signals are summarized in Table 9. In the downlink, primary and secondary synchronization signals encode the cell identification, allowing the UE to identify and synchronize with the network.

In both the downlink and the uplink there are reference signals (RS), known as pilot signals in other standards, which are used by the receiver to estimate the amplitude and phase flatness of the received signal. The flatness is a combination of errors in the transmitted signal and additional imperfections that are due to the radio channel. Without the use of the RS, phase and amplitude shifts in the received signal would make demodulation unreliable, particularly at high modulation depths such as 16QAM or 64QAM. In these high modulation cases, even a small error in the received signal amplitude or phase can cause demodulation errors.

Table 9. LTE physical signals

Downlink physical signals	**Purpose**
Primary synchronization signal	Used for cell search and identification by the UE. Carries part of the cell ID (one of three orthogonal sequences)
Secondary synchronization signal	Used for cell search and identification by the UE. Carries the remainder of the cell ID (one of 168 binary sequences)
Reference signal	Used for downlink channel estimation. Exact sequence derived from cell ID (one of 3 x 168 = 504 pseudo random sequences)
Uplink physical signals	**Purpose**
Reference signals (demodulation and sounding)	Used for synchronization to the UE and for UL channel estimation

3.2 Physical channels and modulation (36.211) (continued)

Alongside the physical signals are physical channels, which carry the user and system information. These are summarized in Table 10. Notice the absence of dedicated channels, which is a characteristic of packet-only systems. The shared channel structure of LTE is closer to HSPA than it is to the original W-CDMA, the latter being based on alloting dedicated channels to single users.

Table 10. LTE physical channels

Downlink channels	**Full name**	**Purpose**
PBCH	Physical broadcast channel	Carries cell-specific information
PMCH	Physical multicast channel	Carries the MCH transport channel
PDCCH	Physical downlink control channel	Scheduling, ACK/NACK
PDSCH	Physical downlink shared channel	Payload
PCFICH	Physical control format indicator channel	Defines number of PDCCH OFDMA symbols per subframe (1, 2, 3, or 4)
PHICH	Physical hybrid ARQ indicator channel	Carries HARQ ACK/NACK
Uplink channels	**Full name**	**Purpose**
PRACH	Physical random access channel	Call setup
PUCCH	Physical uplink control channel	Scheduling, ACK/NACK
PUSCH	Physical uplink shared channel	Payload

3.2.1 Frame structure

The physical layer supports the two multiple access schemes previously described: OFDMA on the downlink and SC-FDMA on the uplink. In addition, both paired and unpaired spectrum are supported using frequency division duplexing (FDD) and time division duplexing (TDD), respectively.

Although the LTE downlink and uplink use different multiple access schemes, they share a common frame structure. The frame structure defines the frame, slot, and symbol in the time domain. Two radio frame structures are defined for LTE and shown in Figures 21 and 22.

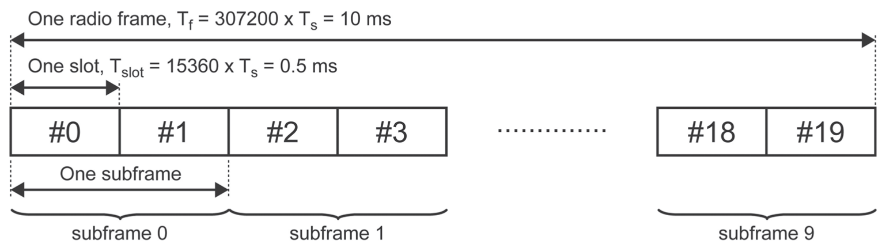

Figure 21. LTE frame structure type 1 (based on 36.211 [10] Figure 4.1-1)

Frame structure type 1 is defined for FDD mode. Each radio frame is 10 ms long and consists of 10 subframes. Each subframe contains two slots. In FDD, both the uplink and the downlink have the same frame structure though they use different spectra.

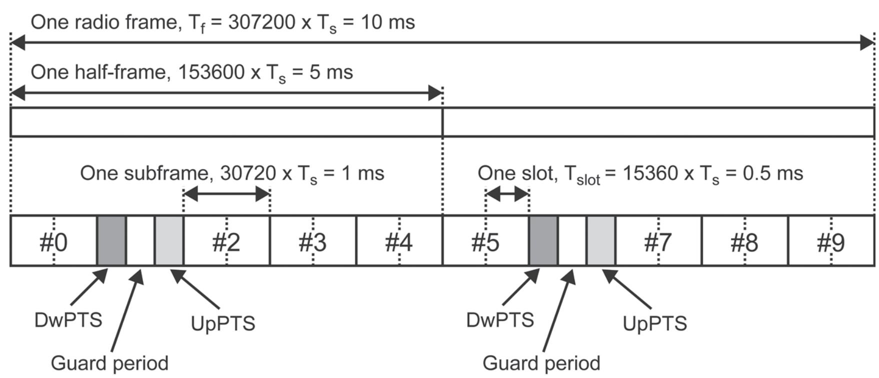

Figure 22. LTE frame structure type 2 for 5 ms switch-point periodicity (based on 36.211 [10] Figure 4.2-1)

Frame structure type 2 is defined for TDD mode. An example is shown in Figure 22. This example is for 5 ms switch-point periodicity and consists of two 5 ms half-frames for a total duration of 10 ms. Subframes consist of either an uplink or downlink transmission or a special subframe containing the downlink and uplink pilot timeslots (DwPTS and UpPTS) separated by a transmission gap guard period (GP). The allocation of the subframes for the uplink, downlink, and special subframes is determined by one of seven different configurations. Subframes 0 and 5 are always downlink transmissions, subframe 1 is always a special subframe, and subframe 2 is always an uplink transmission. The composition of the other subframes varies depending on the frame configuration. For a 5 ms switch-point configuration, subframe 6 is always a special subframe as shown in Figure 22. With 10 ms switch-point periodicity, there is only one special subframe per 10 ms frame.

3.2.2 OFDM symbol and cyclic prefix

One of the key advantages in OFDM systems (including SC-FDMA in this context) is the ability to protect against multipath delay spread. The long OFDM symbols allow the introduction of a guard period between each symbol to eliminate inter-symbol interference due to multipath delay spread. If the guard period is longer than the delay spread in the radio channel, and if each OFDM symbol is cyclically extended into the guard period (by copying the end of the symbol to the start to create the cyclic prefix), then the inter-symbol interference can be completely eliminated.

Figure 23 shows the seven symbols in a slot for the normal cyclic prefix case.

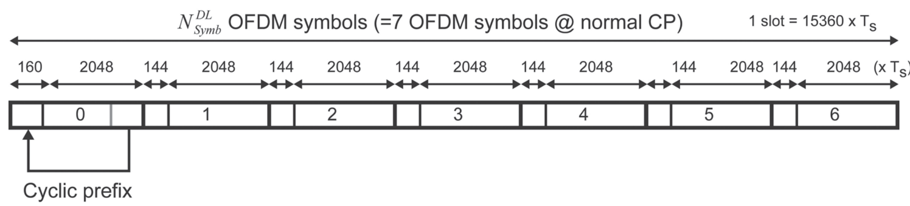

Figure 23. OFDM symbol structure for normal prefix case (downlink)

Cyclic prefix lengths for the downlink and the uplink are shown in Table 11. In the downlink case, Δf represents the 15 kHz or 7.5 kHz subcarrier spacing. The normal cyclic prefix of 144 x T_s protects against multi-path delay spread of up to 1.4 km. The longest cyclic prefix provides protection for delay spreads of up to 10 km.

Table 11. OFDM (downlink) and SC-FDMA (uplink) cyclic prefix length
(based on 36.211 [10] Tables 6.12-1 and 5.6-1)

OFDM configuration (downlink)		**Cyclic prefix length $N_{CP,l}$**
Normal cyclic prefix	Δf = 15 kHz	160 for l = 0 144 for l = 1,2,...,6
Extended cyclic prefix	Δf = 15 kHz	512 for l = 0,1,...,5
	Δf = 7.5 kHz	1024 for l = 0,1,2
SC-FDMA configuration (uplink)		**Cyclic prefix length $N_{CP,l}$**
Normal cyclic prefix		160 for l = 0 144 for l = 1,2,...,6
Extended cyclic prefix		512 for l = 0,1,...,5

3.2.3 Resource element and resource block

A resource element is the smallest unit in the physical layer and occupies one OFDM or SC-FDMA symbol in the time domain and one subcarrier in the frequency domain. This is shown in Figure 24.

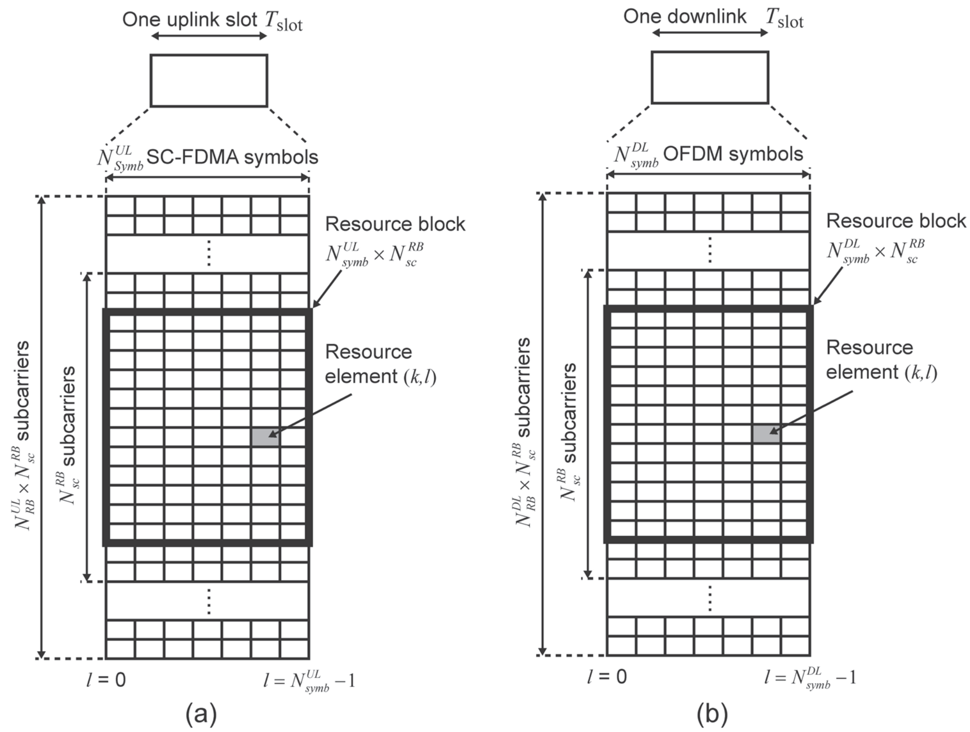

Figure 24. Resource grid for uplink (a) and downlink (b) (36.211 Figures 5.2.1-1 and 6.2.2-1)

A resource block (RB) is the smallest unit that can be scheduled for transmission. An RB physically occupies 0.5 ms (1 slot) in the time domain and 180 kHz in the frequency domain. The number of subcarriers per RB and the number of symbols per RB vary as a function of the cyclic prefix length and subcarrier spacing, as shown in Table 12. The obvious difference between the downlink and uplink is that the downlink transmission supports 7.5 kHz subcarrier spacing, which is used for multicast/broadcast over single frequency network (MBSFN). The 7.5 kHz subcarrier spacing means that the symbols are twice as long, which allows the use of a longer CP to combat the higher delay spread seen when receiving from multiple MBSFN cells.

Table 12. Physical resource block parameters (36.211 [10] Tables 6.2.3-1 and 5.2.3-1)

Downlink configuration		N_{sc}^{RB}	N_{symb}^{DL}
Normal cyclic prefix	Δf = 15 kHz	12	7
Extended cyclic prefix	Δf = 15 kHz		6
	Δf = 7.5 kHz	24	3
Uplink configuration		N_{sc}^{RB}	N_{symb}^{UL}
Normal cyclic prefix		12	7
Extended cyclic prefix		12	6

3.2.4 Example: FDD downlink mapping to resource elements

The primary and secondary synchronization signals, reference signals, PDSCH, PBCH, and PDCCH are almost always present in a downlink radio frame. There is a priority rule for allocation (physical mapping) as follows. Signals (reference signal, primary/secondary synchronization signal) take precedence over the PBCH. The PDCCH takes precedence over the PDSCH. The PBCH and PDCCH are never allocated to the same resource elements, thus they are not in conflict.

Figures 25 and 26 show an LTE FDD mapping example. The primary synchronization signal is mapped to the last symbol of slot #0 and slot #10 in the central 62 subcarriers. The secondary synchronization signal is allocated in the symbol just before the primary synchronization signal. The reference signals are located at symbol #0 and symbol #4 of every slot. The reference signal takes precedence over any other allocation.

The PBCH is mapped to the first four symbols in slot #1 in the central 6 RB. The PDCCH can be allocated to the first three symbols (four symbols when the number of RB is equal or less than 10) of every subframe as shown in Figure 25. The remaining unallocated areas can be used for the PDSCH. Note how the five subcarriers on either side of the primary and secondary synchronous signals remain unallocated.

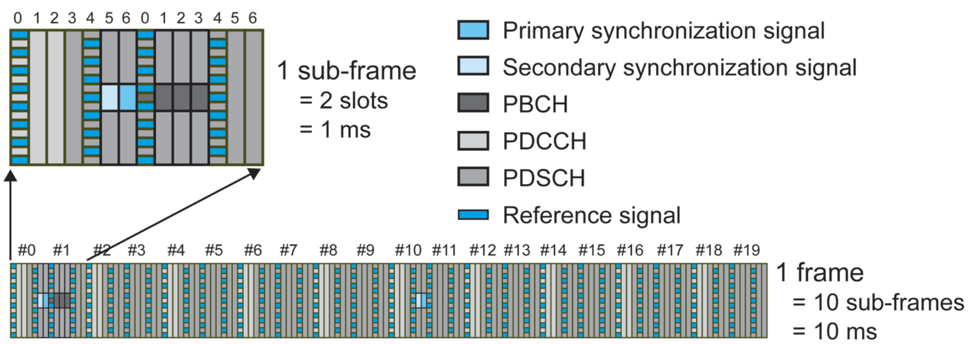

Figure 25. Example of downlink mapping (normal cyclic prefix)

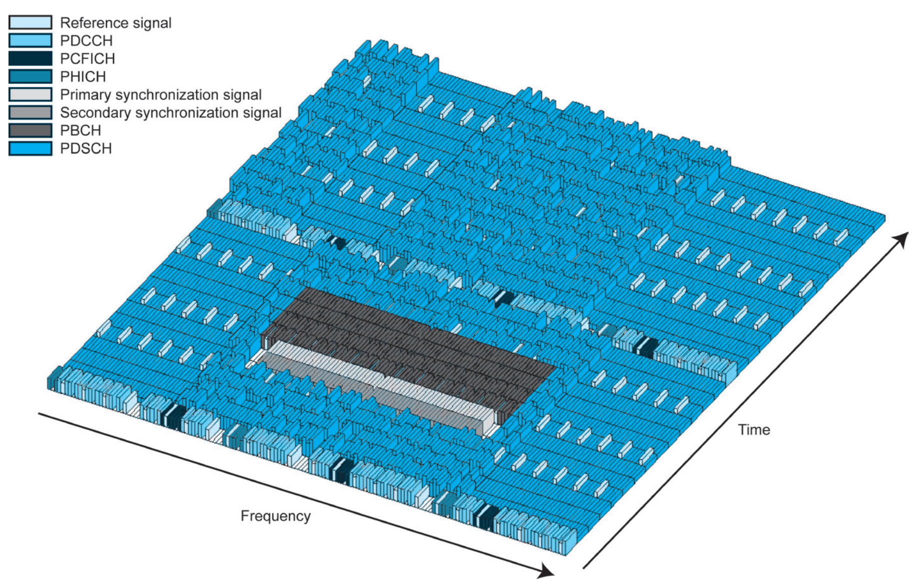

Figure 26. Example of downlink mapping showing frequency (subcarriers) vs. time

3.2.5 Example: Uplink mapping to resource elements

Figure 27 shows an example of an uplink mapping. The spectrum for the uplink is shared by multiple UE in the time domain and frequency domain. A resource is usually allocated for a UE as a unit of RB. In some cases, the same RB in time is allocated to multiple UEs, which are identified using orthogonal spreading codes as in CDMA.

The constellations for PUCCH and the DMRS for PUCCH and PUSCH may be rotated based on parameters given by higher layers; for example, cyclic shift and sequence index. The constellations shown in Figure 27 are without rotation.

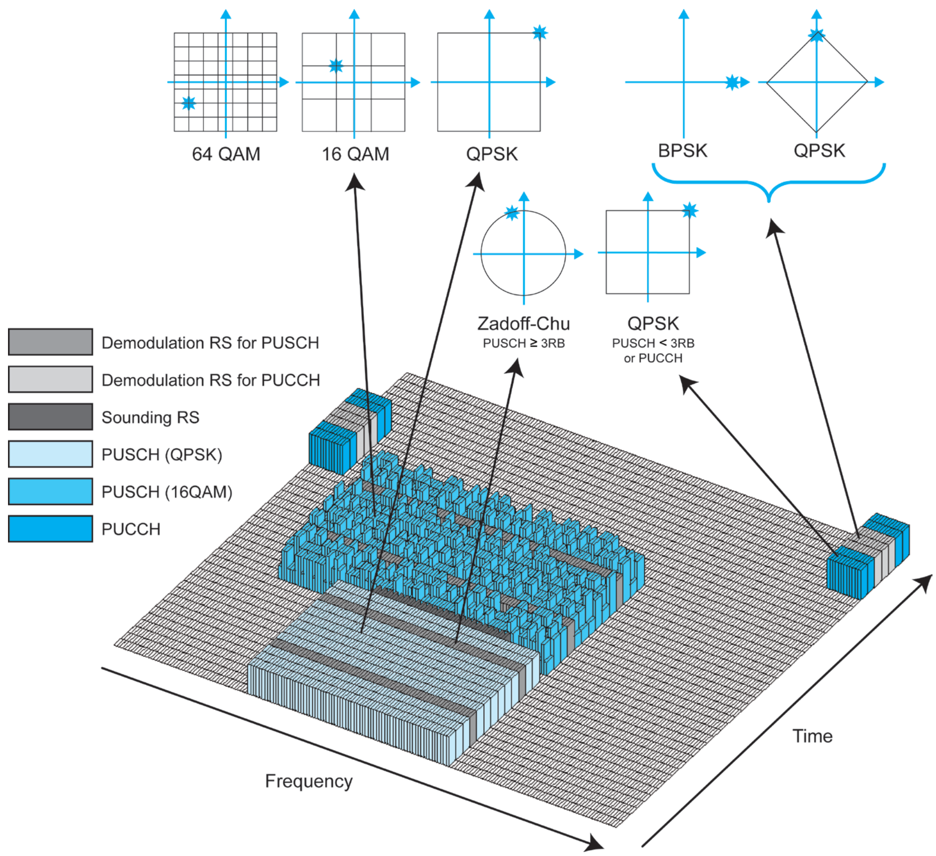

Figure 27. Example of uplink mapping showing frequency (subcarriers) vs. time

3.2.6 Example: TDD mapping to resource elements

Figures 28 and 29 show examples of 5 ms and 10 ms TDD switch point periodicity. The primary synchronization signal is mapped to the third symbol of slot #2 and slot #12 in the central 62 subcarriers. The secondary synchronization signal is allocated in the last symbol of slot #1 and slot #11. The reference signals are located at symbol #0 and symbol #4 of every slot. The reference signal takes precedence over any other allocation. The PBCH is mapped to the first four symbols in slot #1 in the central 6 RB. The PDCCH can be allocated to the first three symbols of every subframe as shown here. The remaining unallocated areas can be used for the PDSCH.

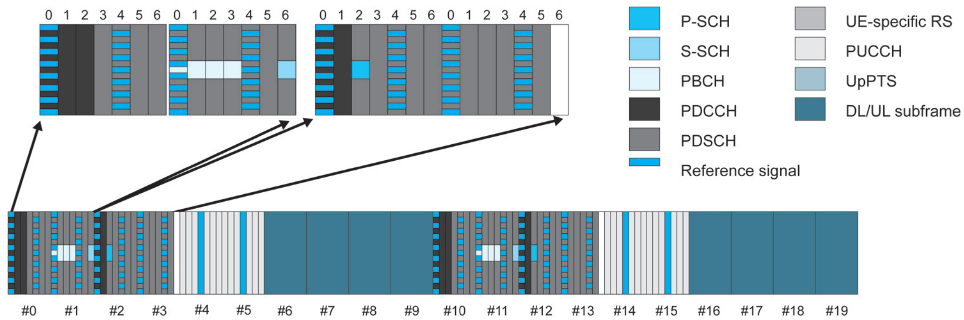

Figure 28. Example of LTE TDD 5 ms switch periodicity mapping

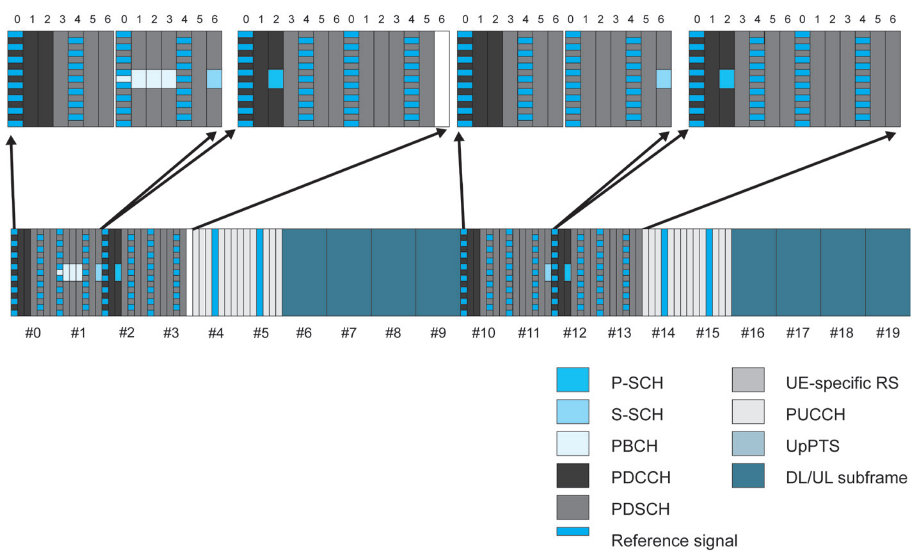

Figure 29. Example of LTE TDD 10 ms switch periodicity mapping

3.2.7 Modulation

The allowed signal and channel modulation schemes for the downlink and uplink are shown in Table 13. Detailed specifications for the physical signals and channels, along with their modulation and mapping, are documented throughout 36.211 [10].

Table 13. Modulation schemes for the LTE downlink and uplink (based on 36.211 [10])

Downlink	
Downlink channels	Modulation scheme
PBCH	QPSK
PDCCH	QPSK
PDSCH	QPSK, 16QAM, 64QAM
PMCH	QPSK, 16QAM, 64QAM
PCFICH	QPSK
PHICH	BPSK modulated on I and Q with the spreading factor 2 or 4 Walsh codes
Physical signals	Modulation scheme
RS	Complex I+jQ pseudo random sequence (length-31 Gold sequence) derived from cell ID
Primary synchronization	One of three Zadoff-Chu sequences
Secondary synchronization	Two 31-bit BPSK M-sequence
Uplink	
Physical channels	Modulation scheme
PUCCH	BPSK, QPSK
PUSCH	QPSK, 16QAM, 64QAM
PRACH	uth root Zadoff-Chu
Physical signals	Modulation scheme
Demodulation RS	Zadoff-Chu
Sounding RS	Based on Zadoff-Chu

3.3 Multiplexing and channel coding (36.212)

The physical layer offers data transport services to the higher layers through transport channels (TrCH) and control information channels. Table 14 lists the types of downlink and uplink TrCH channels, which are defined in 36.212, and Table 15 lists the control information defined in the same document.

Table 14. Transport channel types

Transport channel type		Functions
Downlink		
Downlink shared channel	DL-SCH	Support for HARQ, dynamic link modulation, dynamic and semi-static resource allocation, UE discontinuous reception, and MBMS transmission Possibility to be broadcast in entire cell coverage area to allow beamforming
Broadcast channel	PBCH	Fixed transport format Must be broadcast in entire cell coverage area
Paging channel	PCH	Support for UE discontinuous reception Must be broadcast in entire cell coverage area, mapped to physical resources
Multicast channel	MCH	Support for MBSFN, semi-static resource al-location Must be broadcast in entire cell coverage area
Uplink		
Uplink shared channel	UL-SCH	Support for dynamic link adaptation, HARQ, dynamic, and semi-static resource allocation Possibility to use beamforming
Random access channel	RACH	Limited control information, collision risk

Table 15. Control information

Downlink	
Control format indicator	CFI
HARQ indicator	HI
Downlink control information	DCI
Uplink	
Uplink control information	UCI

3.3 Multiplexing and channel coding (36.212) (continued)

TrCH and control channel information is mapped to the corresponding physical channels as shown in Table 16.

Table 16. Mapping to physical channels
(based on 36.212 [12] Tables 4.2-1 and 4.1-1])

Downlink	
TrCH	**Physical channel**
DL-SCH	PDSCH
BCH	PBCH
PCH	PDSCH
MCH	PMCH
Control information	**Physical channel**
CFI	PCFICH
HI	PHICH
DCI	PDCCH
Uplink	
TrCH	**Physical channel**
UL-SCH	PUSCH
RACH	PRACH
Control information	**Physical channel**
UCI	PUCCH, PUSCH

3.3.1 Channel coding

The data and control streams to and from the MAC layer are encoded and decoded using channel coding schemes. Channel coding is a combination of error detection, segmentation, error correction, rate matching, concatenation, and interleaving.

Channel coding gives forward error correction (FEC) to the transport channel and control information. Two channel coding schemes are used in LTE for the TrCH: turbo coding for the UL-SCH, DL-SCH, PCH, and MCH; and tail-biting convolutional coding for the BCH. For both schemes, the coding rate is R = 1/3 (that is, for every bit that goes into the coder, three bits come out).

Control information is coded using various schemes, including tail-biting convolutional coding, block code, repetition code, and various coding rates.

Precise details of the physical layer processing for transport channels vary by TrCH type and are specified throughout 36.212.

3.3.2 HARQ and AMC

Latency and throughput are two important measures of performance for digital communication systems. LTE uses a number of mechanisms in the physical layer to improve performance in both of these areas; notably, hybrid automatic repeat requests (HARQ) processing and adaptive modulation and coding (AMC).

HARQ is a technique for ensuring that data is sent reliably from one network node to anther, identifying when transmission errors occur and facilitating retransmission from the source. LTE uses Type-II HARQ protocols, similar to HSPA and HSPA+.

AMC is the mechanism used for link adaptation to improve data throughput in a faded channel. This technique varies the downlink modulation coding scheme based on the channel conditions of each user. When the link quality is good, the LTE system can use a higher order modulation scheme (more bits per symbol) or less channel coding, which results in higher data rates. When link conditions are poor because of problems such as signal fading or interference, the system can use a lower modulation depth or stronger channel coding to maintain acceptable margin in the radio link budget.

Type-II HARQ and AMC work together to provide a very adaptive transport mechanism in LTE. Adaptive modulation and coding tunes the initial HARQ transmission to use a coding rate that results in approximately the ideal frame error rate from a throughput perspective. Type-II HARQ then uses incremental redundancy to add redundancy bits for each successive retransmission, thereby reducing the effective code rate until the packet can be decoded correctly. The result, although not perfect, is a means of optimizing the overall throughput over wide ranges of dynamically changing channel conditions while holding latency to a minimum.

3.4 Physical layer procedures (36.213)

A number of physical layer procedures are associated with LTE operation and defined in 36.213 [13]. The general principles of the main procedures are outlined here. Details relate mainly to FDD operation, but TDD is also covered in the specifications.

3.4.1 Synchronization procedures

Two synchronization procedures are identified: cell search and timing synchronization. Cell search is the procedure by which a UE acquires time and frequency synchronization with a cell and detects that cell's physical layer cell ID. To enable cell search the eNB transmits the primary synchronization signal and secondary synchronization signal. Because the synchronization signals are located in the central part of the channel, one LTE cell search procedure supports a scalable overall transmission bandwidth of 6 or more RBs.

Timing synchronization procedures include radio link monitoring, inter-cell synchronization, and transmission timing adjustments.

3.4.2 Power control

Power control procedures include the uplink power control and downlink power allocation. Power control determines the energy per resource element (EPRE). Power control in OFDMA systems is less critical than in CDMA systems, since in OFDMA the UE are separated in time and frequency whereas in CDMA they share the same physical channel and are separated by spreading code, which requires much tighter limits on received power. The importance of power control grows with MU-MIMO, which works best when the received power from each UE at the eNB is balanced.

For the uplink, detailed definitions of power control involving upwards of nine parameters cover the PUSCH, PUCCH, and sounding reference signal (SRS). Special procedures apply to the RB allocated to UEs at the cell edge, where the UEs are most sensitive to inter-cell interference.

For the downlink, all power is referenced to the RS, which is transmitted at constant power across the entire system channel bandwidth. The ratio between the RS EPRE and the PDSCH for one user is settable. Boosting the RS is also supported.

3.4.3 Random access procedures

These procedures cover the transmission of the random access preamble (carried on the PRACH) and the random access response. A PRACH occupies six resource blocks in a subframe or set of consecutive subframes reserved for random access preamble transmissions.

3.4.4 PDSCH-related procedures

The first procedure defines the way in which the PDCCH allocates resources to the UE for receiving the PDSCH. There are three types of allocation mechanisms varying from a simple bitmap (type 0) through the most complex (type 2), which also has the most flexibility.

Additional procedures define how the UE reports the channel quality indicator (CQI), the precoding matrix indicator (PMI), and the rank indication (RI). These reports can be periodic or aperiodic. The CQI is used to report the UE-perceived channel quality. For a single antenna, the CQI is a five-bit index in a table of 32 CQI values that define the modulation scheme and channel coding rate. For increased performance a frequency- selective report, known as subband CQI, can be created by splitting the channel into several subbands. The number of subbands depends on the channel bandwidth and is shown in Table 17. Alternatively the entire channel can be reported once as wideband CQI.

Table 17. Subband size versus downlink system bandwidth (based on 36.213 [13] Table 7.2.1-3)

System bandwidth (resource blocks)	Subband size (k)
6–7	(wideband CQI only)
8–10	4
11–26	4
27–63	6
64–110	8

Periodic CQI reports can be carried on the PUCCH when the UE is not scheduled for transmission and on the PUSCH when the UE is scheduled. The PUCCH has only a few bits of capacity but the PUSCH is much less limited. Aperiodic reports are always carried on the PUSCH. If the scheduling of periodic and aperiodic reports collide, the aperiodic reports always take precedence. The shorter PUCCH report always contains independently useful information for the eNB, whereas the PUSCH reports contain more data and can only be decoded from several transmissions.

There are numerous options for CQI reporting of both PUCCH and PUSCH including UE-assisted subband selection and periodic reporting of different wideband CQI types. When compared to the single CQI report of HSDPA, LTE has a massively more complex reporting structure with the potential for increased performance.

The PMI report is used in conjunction with MIMO to indicate to the eNB which of the available precoding matrices would result in the best performance. The PMI can be a single value or multiple subband values configured by the network for specific RBs. The PMI carries an index to a codebook of predetermined precoding matrices. For the simplest downlink configuration of 2x2 SU-MIMO there are four possible matrices but only three are defined. For the most complex 4x4 configuration there are 16 matrices that cover MIMO for Rank = 2 and beamsteering when Rank = 1.

3.4.4 PDSCH-related procedures (continued)

RI defines the preferred number of parallel MIMO data streams and is always reported as a single wideband value for the channel. This significantly reduces the amount of feedback data since RI affects the CQI and PMI. RI reporting is needed about once per frame (10 ms) and is slower than CQI and PMI reporting that can be done at the subframe rate.

3.4.5 PUSCH-related procedures

The UE allocation for transmission of the PUSCH is provided by a scheduling grant message carried on the PDCCH, providing the UE with the starting RB and length of contiguous RB for PUSCH transmission.

The UE transmission of SRS for uplink channel estimation is used when no PUCCH or PUSCH are scheduled. Parameters provided by the upper layers include SRS periodicity and duration, symbol location in the subframe, frequency hopping, cyclic shift, and repetition factors.

3.4.6 PDCCH-related procedures

The UE is required to monitor the downlink for the presence of the PDCCH. The PCFICH indicates the number of PDCCH symbols (1, 2, or 3) in each subframe to monitor and the PHICH symbol duration, which is read from the P-BCH. The PHICH duration is less than or equal to the number of PDCCH symbols and is 1 or 3 for unicast operation, and 1 or 2 for MBSFN operation.

3.4.7 PUCCH-related procedures

The position of the ACK/NACK sent in the PUCCH for scheduled PSDSCH transmissions is determined implicitly from the associated PDCCH. For a PDSCH detected in subframe n, the associated ACK/NACK messages are transmitted in subframe n+4. This delay is a key parameter in determining the overall latency for retransmission, which is eight subframes (8 ms).

3.5 Physical layer measurements (36.214)

The UE and the eNB are required to make physical layer measurements of the radio characteristics. The measurement definitions are specified in 36.214 [14]. Measurements are reported to the higher layers and are used for a variety of purposes including intra- and inter-frequency handover, inter-radio access technology (inter-RAT) handover, timing measurements, and other purposes in support of RRM.

Although the physical layer measurements are defined in 36.214 [14], the measurement conditions and accuracy requirements are provided in subclauses 9 and 10 of the RRM specification 36.133 [15].

3.5.1 UE physical layer measurements

The UE physical layer measurements are all either measures of absolute power or power ratios. They are defined for operation within LTE-only systems. In addition, to enable interworking of LTE with other radio access technologies, LTE UE must have the ability to measure equivalent parameters from the other systems LTE is defined to work with. These are UMTS FDD, UMTS TDD, GSM, and cdma2000® based systems.

Reference signal receive power

Reference signal receive power (RSRP) is the most basic of the UE physical layer measurements and is the linear average (in watts) of the downlink reference signals (RS) across the channel bandwidth. Since the RS exist only for one symbol at a time, the measurement is made only on those resource elements (RE) that contain cell-specific RS. It is not mandated for the UE to measure every RS symbol on the relevant subcarriers. Instead, accuracy requirements have to be met. There are requirements for both absolute and relative RSRP. The absolute requirements range from ±6 to ±11 dB depending on the noise level and environmental conditions. Measuring the difference in RSRP between two cells on the same frequency (intra-frequency measurement) is a more accurate operation for which the requirements vary from ±2 to ±3 dB. The requirements widen again to ±6 dB when the cells are on different frequencies (inter-frequency measurement).

Knowledge of absolute RSRP provides the UE with essential information about the strength of cells from which path loss can be calculated and used in the algorithms for determining the optimum power settings for operating the network. Reference signal receive power is used both in idle and connected states. The relative RSRP is used as a parameter in multi-cell scenarios.

Reference signal receive quality

Although RSRP is an important measure, on its own it gives no indication of signal quality. Reference signal receive quality (RSRQ) provides this measure and is defined as the ratio of RSRP to the E-UTRA carrier received signal strength indicator (RSSI). The E-UTRA carrier RSSI parameter represents the entire received power including the wanted power from the serving cell as well as all co-channel power and other sources of noise. Measuring RSRQ becomes particularly important near the cell edge when decisions need to be made, regardless of absolute RSRP, to perform a handover to the next cell. Reference signal receive quality is used only during connected states. Intra- and inter-frequency absolute RSRQ accuracy varies from ±2.5 to ±4 dB, which is similar to the interfrequency relative RSRQ accuracy of ±3 to ±4 dB.

UTRA FDD CPICH received signal code power

Received signal code power (RSCP) is inherited from UMTS and is a measure of the absolute power of one code channel within the overall UTRA CDMA signal. UTRA FDD CPICH RSCP is therefore a measure of the code power of the common pilot indicator channel (CPICH) and is used for interworking between LTE and UMTS. It has the same basic function as RSRP in LTE and is used in LTE inter-RAT idle and inter-RAT connected states.

UTRA FDD carrier received signal strength indicator

UTRA FDD received signal strength indicator (RSSI) is also inherited from UMTS. It is a measure of the total received power, including thermal noise and noise generated in the receiver, within the bandwidth defined by the receiver pulse shaping filter. It is the UTRA equivalent of the E-UTRA carrier RSSI defined as part of the reference signal received quality (RSRQ).

UTRA RDD CPICH E_C/N_0

This final measurement from UMTS is the ratio of the CPICH to the power density in the channel. If receive diversity is not being used by the UE, CPICH EC/N0 is the same as CPICH RSCP divided by RSSI. A typical value in a UMTS cell without significant noise would be around –10 dB; indicating the CPICH had been set 10 dB below the total power of the cell. UTRA FDD CPICH EC/N0 is used in LTE inter-RAT idle and connected states.

GSM carrier RSSI

When LTE has to interwork with GSM-based systems including GPRS and E-GPRS (EDGE), the GSM version of RSSI must be measured. GSM RSSI is measured on the broadcast control channel (BCCH). It is used in LTE inter-RAT idle and connected states.

UTRA TDD carrier RSSI

This measurement is used for interworking with UTRA TDD systems and performs the same basic function as the other RSSI measurements. It is used in LTE inter-RAT idle and connected states.

UTRA TDD P-CCPCH RSCP

This measurement is the UTRA TDD equivalent of RSRP. It is a measure of the code power of the Primary Common Control Physical Channel (P-CCPCH) and is used in LTE inter-RAT idle and connected states.

cdma2000 1xRTT pilot strength

This measurement is the RSRP equivalent for cdma2000-based technologies. These technologies all share the same radio transmission technology (RTT) bandwidth based on the 1.2288 Mcps chip rate that is referred to as 1x. Multi-carrier versions of cdma2000 such as 3xRTT have been standardized but no multicarrier measurement is yet defined. The cdma2000 pilot is carried on Walsh code 0, typically at around –7 dB from the total downlink power.

cdma2000 high rate packet data pilot strength

High rate packet data (HRPD) systems including 1xEV-DO Releases 0, A and B do not use the code domain pilot signal defined for the speech-capable cdma2000. The cdma2000 HRPD pilot is defined in the time domain, existing for 9.375% of the frame. Its measurement is therefore necessary for LTE interworking with HRPD systems and is another version of LTE RSRP.

3.5.1 UE physical layer measurements (continued)

Additional UE measurements for the support of positioning

In Release 9 a number of new measurements were defined for the support of positioning.

- Reference signal time difference (RSTD) is a measure of the time difference between the RS of different cells used for the observed time difference of arrival (OTDOA) positioning system.
- Global navigation satellite system (GNSS) timing of cell frames for UE positioning is a measurement between an E-UTRA cell as detected by the UE and the GNSS time for a specific GNSS identified by the UE.
- UE GNSS code measurement is a measure of the spreading code phase of a GNSS satellite signal.
- UE Rx–Tx time difference is a measure of the time difference between a downlink radio frame and the transmission time of the equivalent uplink frame.

3.5.2 eNB physical layer measurements

There are fewer physical layer measurements for the eNB than for the UE, primarily because the base station is not mobile and does not need to measure non-LTE systems.

Downlink RS Tx power

The first eNB measurement is different in two respects from the UE measurements described so far: first, it describes the eNB transmission itself rather than a transmission from another entity, and second, it is not so much a measurement as a report generated by the eNB reflecting the transmitted power. Even so, the report has to be accurate and take into account losses between the baseband (where power is defined) through the transmit chain to the antenna connector.

Received interference power

The uplink received interference power is a measure of the interference power and thermal noise within an RB that is not scheduled for transmission within the cell. The absolute accuracy has to be ±4 dB for interference measured between –117 dBm and –96 dBm. This measure will be used to identify narrowband co-channel interference from neighbor cells on the same frequency.

Thermal noise power

The uplink thermal noise power measurement is a broadband version of received interference power and is measured optionally at the same time under the same conditions. The definition is (N_0*W) where N_0 is the white noise power spectral density and W is the transmission bandwidth configuration.

Additional eNB measurements for the support of positioning

Release 9 additions for the support of positioning by the eNB are as follows:

- Timing advance (TADV), which comes in two forms. Type 1 is the eNB Rx–Tx timing difference added to the UE Rx–Tx timing difference. Type 2 is just the eNB Rx–Tx timing difference.
- eNB Rx–Tx timing difference, which is a measure of the time difference between an uplink radio frame and the transmission time of the equivalent downlink frame.
- E-UTRAN GNSS timing of cell frames for UE positioning, which is a measurement between the transmit timing of an E-UTRA cell and a specific reference time of a GNSS cell.
- Angle of arrival (AoA), which defines the estimated angle of a user with respect to a reference direction relative to geographic North in counter-clockwise direction.

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3.6 Radio resource management (36.133)

The requirements for RRM are defined in 36.133 [15] and are divided into two major parts. First are the individual performance requirements for the core functions supporting RRM. These are defined in subclauses 4 through 10. Second, Annex A provides normative test case descriptions that will be used as the basis for the RRM conformance tests. These test cases combine many of the underlying core requirements into typical operating scenarios, which is preferable to testing each function individually. Subclauses 9 and 10 specify requirements for the physical layer measurements described in Section 3.5.

3.6.1 E-UTRAN RRC_IDLE state mobility

Refer to 36.133 [15] subclause 4. This section covers the two most basic of procedures carried out when the UE is in idle state (not on a call). These procedures are cell selection, which is performed after the UE is switched on, and cell re-selection, which is the procedure performed when the UE moves from one cell to another.

Cell selection

The most obvious parameter to specify for cell selection performance is the time taken to camp onto an appropriate cell for a given radio scenario. One of the most complex scenarios commonly occurs when the UE is switched on in a rich radio environment; for example, in a foreign airport where competition for roaming customers can be fierce. There are many ways of configuring parameters in the network that can influence the behavior of the UE when it initially chooses a cell on which to camp. It is perhaps due to the complexity of the cell selection process that in UMTS, no requirements were specified. It is likely that LTE will take the same approach. This might seem surprising but as things stand, this aspect of UE performance is left as a competitive rather than a regulated issue.

Cell re-selection

For cell re-selection, the situation is quite different as LTE specifies numerous performance requirements for this process. When the UE is camped on the serving cell, it will be commanded to detect, synchronize and monitor intra-frequency, inter-frequency and inter-RAT cells to determine whether a more suitable cell on which to camp can be found. Sometimes the serving cell will provide a neighbor list for the intra-frequency and inter-frequency LTE cells, but at other times only the carrier frequency and bandwidth will be provided. The rules for neighbor cell reporting allow the UE to limit its measurement activity in complex situations.

3.6.1 E-UTRAN RRC_IDLE state mobility (continued)

The goal of the cell re-selection process is the evaluation of the cell selection criterion S for each detected cell. This measure is based on relative and absolute power measurements and is used to determine the most favorable cell for the UE to camp on. The cell re-selection performance requirements are defined in terms of three time allowances: the time allowed to detect and evaluate S for a new cell, the time allowed to re-evaluate S for an existing cell and the maximum time allowed between measurements of the cell. One of the important parameters impacting cell re-selection performance is the discontinuous reception (DRX) cycle length. This is the time between attempts by the UE to measure cells other than the serving cell. There is clearly a trade-off between a long DRX cycle that does not interrupt normal operation in the serving cell but gives slow re-selection times, and a much shorter DRX cycle that speeds up detection but interrupts normal operation. The defined DRX cycle lengths in seconds are 0.32, 0.64, 1.28 and 2.56.

The cell re-selection rules are complex and are only briefly described here. The UE is required to continuously monitor the serving cell and should it fail to fulfill the cell selection criteria, the UE has to immediately measure all the neighbor cells indicated by the serving cell, regardless of any rules currently limiting UE measurements. The UE is required to identify detectable intra-frequency E-UTRAN cells and measure the RSRP without prior knowledge of the physical cell identity. Cells are considered detectable if they exceed certain absolute power and SNR limits. For detectable cells, the key performance requirement is the time allowed to evaluate the cell selection criterion S. The rules for inter-frequency E-UTRAN cells have additional complexity but the key performance requirement remains the time taken to evaluate S.

As might be expected the situation gets significantly more complex for inter-RAT cell re-selection. Cell re-selection performance requirements exist for UTRA FDD, UTRA TDD, GSM, HRPD and cdma2000 1xRTT. The specification of further RATs is likely in the future.

3.6.2 E-UTRAN RRC_CONNECTED state mobility

Refer to 36.133 [15] subclause 5. The requirements for mobility while connected are more generally known by the term handover. The combinations of handover for which performance requirements have been defined fall into two categories:

E-UTRAN handover

E-UTRAN FDD to FDD
E-UTRAN FDD to TDD
E-UTRAN TDD to FDD
E-UTRAN TDD to TDD

Handover to other RAT

E-UTRAN to UTRAN FDD
E-UTRAN to UTRAN TDD
E-UTRAN to GSM
E-UTRAN to HRPD
E-UTRAN to cdma2000 1xRTT

For each scenario two performance parameters are defined. These are the handover delay and the interruption time. Both parameters are necessary as the first is a measure of the delay from the start of the process to its completion and needs to be kept low, while the second parameter is the shorter period of time during which communication is interrupted.

3.6.3 RRC connection mobility control

Refer to 36.133 [15] subclause 6. The requirements for RRC connection mobility control are for RRC re-establishment following a failure in the RRC connection and for random access. The most likely causes of a failure are if the radio link drops below an acceptable quality or if a handover fails. The requirements are written based on the time allowed to re-establish the RRC connection.

The reestablishment delay is determined by four parameters: the number of frequencies being monitored, the time to search each frequency, the time to read the system information from each cell and the delay in the PRACH procedure. For simple cases in which the target cell is known by the UE and has been recently measured, the delay may be as short as 160 ms. More difficult situations that require searching for a suitable cell on which to reestablish the link could be in the order of one second per frequency searched.

The requirements for random access relate to correct behavior when a random access response and other messages are received from the eNB.

3.6.4 Timing and signaling characteristics

Refer to 36.133 [10] subclause 7.

UE transmit timing

A critical performance requirement in any wireless system is the ability of the UE to maintain timing synchronization with the base station. The unit for measuring timing is T_s, where $T_s = 1/(15000*2048)$ seconds. The timing reference point for the UE is the first detected path from the eNB. The nominal transmit timing of the UE is specified in advance of this reference time as $N_{TA}* T_s$, where N_{TA} is the timing advance parameter.

Requirements exist for the initial timing accuracy, the maximum step in any one timing adjustment and finally the maximum and minimum timing adjustment rates. These requirements are necessary in order that the worst case timing error between the eNB and UE is bounded. Timing errors can be caused by large changes in multipath delay (such as with shadow fading) or by a handover to a cell with different timing.

The initial timing accuracy requirement is $\pm 12* T_s$ and should this be exceeded, the UE is required to adjust its timing to get to within the allowed range. During the adjustment process the maximum allowed step size is $\pm 2* T_s$ and the rate of change has to be between $2* T_s$ and $7* T_s$ seconds per second.

UE timer accuracy

Many of the RRM processes require that the UE start and stop various timers. For timers of less than four seconds the accuracy is fixed at 0.1 seconds and for longer timers the UE is given a greater allowance of 0.25%. These are not critical figures but are specified in order to give guidance to the UE designer about the precision required for timer implementation.

Timing advance

When the UE receives a new timing advance command in frame number n it is required to implement the new timing in frame $n + 6$ to an accuracy of $\pm 4* T_s$.

Cell phase synchronization accuracy (TDD)

In TDD systems, this requirement controls the frame start timing for any two cells that share the same frequency and overlap coverage areas. It is necessary to control the timing between such cells to avoid the transmission from one cell occurring at the same time as reception by the other. The requirement for wide area base stations that have a cell radius ≤ 3 km is ≤ 3 µs. This requirement is relaxed to ≤ 10 µs for cell radius above 3 km. For home base stations, the timing requirement is ≤ 3 µs for a cell radius of ≤ 500 m. For larger cells, the requirement is ≤ 1.33 µs plus $T_{propagation}$, which is the propagation delay between the home base station and the cell selected as the network listening synchronization source.

3.6.4 Timing and signaling characteristics (continued)

Synchronization requirements for E-UTRAN to cdma2000 1xRTT/HSPD handovers

In order for successful handover to cdma2000 1xRTT and HRPD it is necessary for the UE to know the CDMA system timing reference. This is achieved by the eNB providing the timing via a system information message. Once the UE knows the system timing, it can report the timing of the target system's pilot signals. The basic requirement is for the eNB to be within ±10 µs of the CDMA system time. The eNB is expected to be synchronized to GPS time and to maintain ±10 µs accuracy for a period of up to 8 hours should GPS synchronization be lost. The eNB also has to ensure that the message transmitting the CDMA system time is transmitted within 10 µs of the expected time.

Radio link monitoring

The UE is required to monitor the quality of the downlink for the purposes of determining if the radio link is good enough to continue transmission. This is done through the parameters Q_{out} and Q_{in}. The threshold for Q_{out} is defined as the level at which the downlink radio link cannot be reliably received. There is no direct measure, but the assumption is that Q_{out} corresponds to an approximate 10% block error ratio of a hypothetical PDCCH transmission taking into account a number of network settings and radio conditions. Q_{in} is defined as having a much higher probability of reception than Q_{out}. The Q_{in} threshold is nominally a 2% block error ratio of the hypothetical PDCCH for a defined set of network settings and radio conditions. The requirements for the UE to monitor the radio link quality are specified in terms of how long the UE takes to switch off when the quality drops below Q_{out} and how long it takes for the UE to switch back on when the quality rises above Q_{in}.

3.6.5 UE measurement procedures in RRC_CONNECTED state

Refer to 36.133 [15] subclause 8. In cellular systems, knowing when and where to make a handover can be difficult. To make good handover decisions requires knowledge of the environment. By measuring and reporting the radio environment when in a connected state, the UE provides the system with the raw material needed to make the correct handover decisions. Many parameters can be measured, and the rules for how and when to gather and report these parameters are complex. The requirements, which are split according to RAT, are the following: E-UTRA intra-frequency, E-UTRA inter-frequency, inter-RAT UTRA FDD, UTRA TDD and GSM. The required measurement accuracy is defined in 36.133 [15] subclause 9.

With the exception of intra-frequency measurements, it is not possible for the UE to gather information on different frequencies or RATs without implementing a transmission gap. During this period the UE is able to retune its receiver (DRX) to monitor other frequencies. The options for configuring the UE can become quite complex, especially when the radio environment includes multiple bands and RATs. Trade-offs have to be made between the desire for full knowledge of the radio environment, which requires frequent gaps, and the desire for less interruption and fewer measurements, which leads to slower and less optimized handover decisions.

4. RF Conformance Tests

The goal of the LTE conformance tests is to ensure a minimum level of performance. For the UE, conformance testing is divided into three parts: RF, RRM, and signaling. For the base station (eNB), only RF conformance tests are defined. This application note is limited to RF conformance testing. Tables 18 and 19 show the key specifications relating to RF conformance tests for the UE and eNB, respectively.

Table 18. UE RF FDD and TDD conformance test specifications

Specification	Title	Purpose
36.124 [16]	Electromagnetic Compatibility (EMC) Requirements for Mobile Terminals and Ancillary Equipment	Tests for EMC emissions and immunity
36.521-1 [17]	User Equipment (UE) Conformance Specification; Radio Transmission and Reception Part 1: Conformance Testing (FDD/TDD)	RF conformance tests primarily based on 36.101 [6]
36.521-2 [18]	User Equipment (UE) Conformance Specification; Radio Transmission and Reception Part 2: Implementation Conformance Statement (ICS)	Definition of applicability of tests for different UE capabilities
36.521-3 [19]	User Equipment (UE) Conformance Specification; Radio Transmission and Reception Part 3: Radio Resource Management Conformance Testing	RRM conformance tests based on 36.133 [15]

Table 19. Base station (eNB) RF FDD and TDD conformance test documents

Specification	Title	Purpose
36.113 [20]	Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) and Repeater Electromagnetic Compatibility (EMC)	Tests for EMC emissions and immunity
36.141 [21]	Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) Conformance Testing	RF conformance tests based primarily on 36.104 [7]
36.143 [22]	Evolved Universal Terrestrial Radio Access (E-UTRA); FDD Repeater Conformance Testing	Repeater conformance tests based primarily on 36.106 [23]

The structure of the UE RF conformance test follows a set pattern that consists of the following steps:

- Test purpose
- Test applicability
- Minimum conformance requirements
- Test description: initial conditions, test procedure, and message contents
- Test requirements

The eNB RF conformance tests cover the same list in a slightly different order, and the message contents are not required since the eNB tests are done without signaling.

4.1 UE RF conformance tests

The UE RF conformance tests defined in 36.521-1 [17] are divided into RF transmitter characteristics, RF receiver characteristics, and RF performance characteristics. The intention here is to provide an overview of the overall scope with some LTE-specific discussion.

4.1.1 UE RF transmitter characteristics

Table 20 lists the transmitter test cases defined in 36.521-1 [17]. Note that the ACLR additional requirements subclause 6.6.2.4 described in previous versions of the specification has been removed.

Table 20. UE RF transmitter test cases

36.521-1 subclause	Test case
6.2.2	UE maximum output power
6.2.3	Maximum power reduction (MPR)
6.2.4	Additional maximum power reduction (A-MPR)
6.2.5	Configured UE transmitted output power
6.3.2	Minimum output power
6.3.3	Transmit OFF power
6.3.4.1	General ON/OFF time mask
6.3.4.2	PRACH and SRS time mask
6.3.5.1	Power control absolute power tolerance
6.3.5.2	Power control relative power tolerance
6.3.5.3	Aggregate power control tolerance
6.5.1	Frequency error
6.5.2.1	Error vector magnitude (EVM)
6.5.2.2	IQ-component
6.5.2.3	In-band emissions for non-allocated RB
6.5.2.4	Spectrum flatness
6.6.1	Occupied bandwidth
6.6.2.1	Spectrum emission mask
6.6.2.2	Additional spectrum emission mask
6.6.2.3	Adjacent channel leakage power ratio (ACLR)
6.6.3.1	Transmitter spurious emissions
6.6.3.2	Spurious emission band UE co-existence
6.6.3.3	Additional spurious emissions
6.7	Transmit intermodulation

4.1.1 UE RF transmitter characteristics (continued)

The scope of these RF transmitter tests will be familiar from UMTS and are modified only in the details as they pertain to LTE and the SC-FDMA uplink modulation format. The transmitter tests are carried out using uplink reference measurement channels (RMCs). The RMCs fall into three main categories—fully allocated, partially allocated, and single RB—and were defined based on the simulation assumptions used to derive the requirements. The number of different RMC configurations defined for testing is a balance between thoroughness and excessive test time.

4.1.2 UE RF receiver characteristics

Table 21 lists the UE receiver test cases defined in 36.521-1 [17].

Table 21. UE RF receiver test cases

36.521-1 subclause	Test case
7.3	Reference sensitivity level
7.4	Maximum input level
7.5	Adjacent channel selectivity (ACS)
7.6.1	In-band blocking
7.6.2	Out-of-band blocking
7.6.3	Narrow band blocking
7.7	Spurious response
7.8.1	Wide band intermodulation
7.9	Spurious emissions

These test cases are similar to the UE RF test cases for UMTS. One difference worth noting is that the receiver minimum requirements for UMTS were typically specified in terms of a bit error ratio (BER) as distinct from the BLER used in the UMTS performance tests. This difference was due to somewhat arbitrary choices made during the early development of UMTS when some requirements simulation work was done using BER and others using BLER. Because a verifiable BER result requires the transmitted data to be looped back to the test system, it is a more difficult measure to make than simply counting the UE's ACK and NACK reports necessary for calculating BLER. That said, BER is more subtle in its ability to pick up small variations in performance compared to BLER and remains a useful measure during product development.

For LTE the receiver minimum requirements are expressed in terms of a percentage throughput (> 95%) of the RMC used in the test. Since BLER can be mapped directly to throughput, the LTE receiver tests are brought in line with the performance tests that have always been based on BLER and throughput.

4.1.3 UE RF performance requirements

The UE RF performance requirements are defined in 36.521-1 [17], as shown in Table 22.

Table 22. UE RF performance test cases

36.521-1 subclause	Test case
8.2.1.1	FDD PDSCH single antenna port performance (cell-specific reference symbols)
8.2.1.2	FDD PDSCH transmit diversity performance (cell-specific reference symbols)
8.2.1.3	FDD PDSCH open loop spatial multiplexing performance (cell-specific reference symbols)
8.2.1.4	FDD PDSCH closed loop spatial multiplexing performance (cell-specific reference symbols)
8.2.2.1	TDD PDSCH single antenna port performance (cell-specific reference symbols)
8.2.2.2	TDD PDSCH transmit diversity performance (cell-specific reference symbols)
8.2.2.3	TDD PDSCH open loop spatial multiplexing performance (cell-specific reference symbols)
8.2.2.4	TDD PDSCH closed loop spatial multiplexing performance (cell-specific reference symbols)
8.3.2.1	TDD PDSCH performance (UE-specific reference symbols)
8.4.1.1	FDD PCFICH/PDCCH single-antenna port performance
8.4.1.2	FDD PCFICH/PDCCH transmission diversity performance
8.4.2.1	TDD PCFICH/PDCCH single-antenna port performance
8.4.2.2	TDD PCFICH/PDCCH transmit diversity performance
8.5.1.1	FDD PHICH single-antenna port performance
8.5.1.2	FDD PHICH transmit diversity performance
8.5.2.1	TDD PHICH single-antenna port performance
8.5.2.2	TDD PHICH transmit diversity performance
8.7.1.1	FDD sustained data rate performance
8.7.2.1	TDD sustained data rate performance
9.2.1.1	FDD CQI reporting under AWGN conditions – PUCCH 1-0
9.2.1.2	TDD CQI reporting under AWGN conditions – PUCCH 1-0
9.2.2.1	FDD CQI reporting under AWGN conditions – PUCCH 1-1
9.2.2.2	TDD CQI reporting under AWGN conditions – PUCCH 1-1
9.3.1.1.1	FDD frequency-selective scheduling mode – PUSCH 3-0
9.3.1.1.2	TDD frequency-selective scheduling mode – PUSCH 3-0
9.3.2.1.1	FDD frequency non-selective scheduling mode – PUCCH 1-0
9.3.2.1.2	TDD frequency non-selective scheduling mode – PUCCH 1-0
9.3.3.1	CQI reporting under fading conditions and frequency-selective interference—PUSCH 3-0 (FDD/TDD)
9.4.1.1.	Single PMI – PUSCH 3-1 (FDD/TDD)
9.4.2.1.	Multiple PMI – PUSCH 1-2 (FDD/TDD)
9.5.1	RI reporting—PUCCH 1-1 (FDD/TDD)
10.1	FDD MBMS performance (fixed reference channel)
10.2	TDD MBMS performance (fixed reference channel)

4.2 UE RRM conformance tests

The RRM requirements are defined in 36.133 [15] and the conformance tests in 36.521-3 [19]. However, as a result of the complexity of the RRM requirements in terms of the number of variables that can affect performance, the core specification (36.133) includes Annex A, which provides guidance on test case configuration for conformance testing. The RRM conformance tests are based on this annex rather than on the core requirements directly. Table 23 lists the RRM test case categories as defined in 36.521-3 [19]. Because of the large number of test cases, individual test cases are not listed.

Table 23. UE RRM test cases

36.521-3 subclause	Test case
4.2	Cell re-selection in E-UTRAN RRC_Idle state
4.3	E-UTRAN to UTRAN cell reselection
4.4	E-UTRAN to GSM cell reselection
4.5	E-UTRAN to HRPD cell reselection
4.6	E-UTRAN to cdma2000 1x cell reselection
5.1	Handover delay in E-UTRAN RRC_Connected state
5.2	E-UTRAN handover to other RATs
5.3	E-UTRAN handover to non-3GPP RATs
6.1	RRC connection mobility control RRC reestablishment
6.2	RRC connection mobility control random access
7.1	Timing and characteristics—UE transmit timing
7.2	Timing and characteristics—UE timing advance
7.3	Timing and characteristics—UE radio link monitoring
8.1	E-UTRAN FDD intra-frequency measurements
8.2	E-UTRAN TDD intra-frequency measurements
8.3	E-UTRAN FDD inter-frequency measurements
8.4	E-UTRAN TDD inter-frequency measurements
8.5	E-UTRAN FDD to UTRAN FDD measurements
8.6	E-UTRAN TDD to UTRAN FDD measurements
8.7	E-UTRAN TDD to UTRAN TDD measurements
8.8	E-UTRAN FDD to GSM measurements
8.9	E-UTRAN FDD to UTRAN TDD measurements
8.10	E-UTRAN TDD to GSM measurements
8.11	Monitoring of multiple layers
9.1	RSRP measurements
9.2	RSRQ measurements
9.3	UTRA FDD CPICH RSCP
9.4	UTRAN FDD CPICH Ec/No
9.6	GSM carrier RSSI

4.3 eNB RF conformance tests

Base station (eNB) conformance testing for LTE is similar to that of UMTS except for those areas of testing affected by the change to using an OFDMA modulation scheme. The eNB RF conformance tests are defined in 36.141 [21] and are based on the core requirements for eNB radio transmission and reception in 36.104 [7]. They are divided into three main sections: RF transmitter characteristics, RF receiver characteristics, and RF performance characteristics.

4.3.1 eNB RF transmitter characteristics

Table 24 lists the eNB RF transmitter characteristics test cases defined in 36.141 [21].

The time alignment test is particularly important for LTE because of the widespread use of transmit diversity, spatial multiplexing, and beamsteering. The requirement for time alignment is 65 ns, which is the same as the UMTS requirement of 1/4 chip (65 ns). The downlink reference signal power test is the equivalent of the CPICH power accuracy test for UMTS.

Table 24. eNB RF transmitter characteristics tests

36.141 [21] subclause	Test case
6.2	Base station output power
6.2.6	Home BS output power for adjacent UTRA channel protection
6.2.7	Home BS output power for adjacent E-UTRA channel protection
6.3.1	Resource element (RE) power control dynamic range
6.3.2	Total power dynamic range
6.4.1	Transmitter OFF power
6.4.2	Transmitter transient period
6.5.1	Frequency error
6.5.2	Error vector magnitude (EVM)
6.5.3	Time alignment between transmitter branches
6.5.4	Downlink reference signal power
6.6.1	Occupied bandwidth
6.6.2	Adjacent channel leakage power ratio (ACLR)
6.6.3	Operating band unwanted emissions
6.6.4	Transmitter spurious emissions
6.7	Transmitter intermodulation

4.3.2 eNB RF receiver characteristics

Table 25 lists the eNB RF receiver characteristics test cases defined in 36.141 [21]. Of note is the in-channel selectivity test, which is unique to OFDMA. This test checks the receiver's ability to maintain a particular throughput on an allocation on one side of the central subcarrier reserved for LO leakage when a larger signal is present on the opposite side. The test checks for IQ distortion in the receiver and is the reverse of the UE transmitter IQ image requirement for in-band emissions.

Table 25. eNB RF receiver characteristics

36.141 [21] subclause	Test case
7.2	Reference sensitivity level
7.3	Dynamic range
7.4	In-channel selectivity
7.5	Adjacent channel selectivity (ACS) and narrow-band blocking
7.6	Blocking
7.7	Receiver spurious emissions
7.8	Receiver intermodulation

4.3.3 eNB RF performance requirements

Table 26 lists the eNB RF performance requirements in 36.141 [21].

Table 26. eNB RF performance tests

36.141 [21] subclause	Test case
8.2.1	Performance requirements of PUSCH in multipath fading conditions
8.2.2	Performance requirements for UL timing adjustment
8.2.3	Performance requirements for HARQ-ACK multiplexed on PUSCH
8.2.4	Performance requirements for High Speed Train conditions
8.3.1	ACK missed detection requirements for PUCCH format 1a
8.3.2	CQI missed detection for PUCCH format 2
8.3.3	ACK missed detection for multi-user PUCCH format 1a
8.4.1	PRACH false alarm probability and missed detection

4.3.4 Downlink test models

The eNB transmitter conformance tests are carried out using downlink configurations known as E-UTRA test models (E-TM). This concept has been inherited from UMTS, although any similarity stops there. The highly flexible nature of the downlink OFDMA modulation scheme means that a large number of parameters are required to fully define any signal. An inspection of the definition of the E-TM in 36.141 [21] subclause 6.1.1 shows how much more complex the signal structure is compared to UMTS. There are three distinct classes of test model defined: E-TM1, E-TM2 and E-TM3. The first and third classes have further subclasses. All test models have the following attributes:

- Single antenna port, single codeword, single layer with no precoding
- Duration of one frame (10 ms)
- Normal cyclic prefix
- Localized virtual resource blocks, no intra-subframe hopping for PDSCH
- Cell-specific reference signals only; no use of UE-specific reference signals

The data content of the PDSCH is generated from a sequence of zeros scrambled using a length-31 Gold code according to 36.211 [10], which also defines the reference signals and the primary and secondary synchronization signals. The physical channels PBCH, PCFICH, PHICH, and PDCCH all have detailed definitions. For each E-TM, the physical signals and physical channels are allocated into the channel at a specific power relative to the RS power. There are six different mappings for each E-TM to account for the six different channel bandwidths. Each E-TM is defined for specific use as shown in Table 27.

Table 27. Evolved Test Model mapping to test cases

E-TM	Notes	Test case
E-TM1.1	Maximum power tests	Output power, occupied bandwidth, ACLR, operating band unwanted emissions, transmitter spurious emissions, transmitter intermodulation, reference signal absolute accuracy
E-TM1.2	Includes power boosting and de-boosting	ACLR, operating band unwanted emissions
E-TM2	Minimum power tests	Total power dynamic range (lower OFDM symbol power limit at min power), EVM of single 64QAM PRB allocation (at min power), frequency error (at min power)
E-TM3.1		Total power dynamic range (upper OFDM symbol power limit at max power with all 64QAM PRBs allocated), frequency error, EVM for 64QAM (at max power)
E-TM3.2	Includes power boosting and de-boosting	Frequency error, EVM for 16QAM
E-TM3.3	Includes power boosting and de-boosting	Frequency error, EVM for QPSK

4.3.5 Uplink fixed reference channels

The eNB receiver and performance tests make use of fixed reference channels (FRCs). The eNB FRCs are, in most cases, single-ended signals that can be generated in a signal generator without the need for any real-time feedback.

Table 28 shows the FRC parameters for 64QAM performance requirements. This example uses a code rate of 5/6, which is intended for testing the highest throughput requirements. For the 100 RB case of A5-7, there are 86,400 bits per 1 ms subframe indicating a maximum throughput of 86.4 Mbps. The eNB performance requirements measured under fading conditions will be based on reaching a percentage of the maximum throughput under particular conditions. For example, 36.141 [21] Table 8.2.1.5-6 indicates that a two channel eNB receiver operating in a pedestrian A channel with 5 Hz Doppler is required to reach 70% of the A5-7 FRC maximum throughput when the SNR is above 19.7 dB.

Table 28. FRC parameters for performance requirements (64QAM 5/6) (36.141 [21] Table A.5-1)

Reference channel	A5-1	A5-2	A5-3	A5-4	A5-5	A5-6	A5-7
Allocated resource blocks	1	6	15	25	50	75	100
DFT-OFDM symbols per subframe	12	12	12	12	12	12	12
Modulation	64QAM	64QAM	64QAM	64QAM	64QAM	64QAM	64QAM
Code rate	5/6	5/6	5/6	5/6	5/6	5/6	5/6
Payload size (bits)	712	4392	11064	18336	36696	55056	75376
Transport block CRC (bits)	24	24	24	24	24	24	24
Code block CRC size (bits)	0	0	24	24	24	24	24
Number of code blocks - C	1	1	2	3	6	9	13
Coded block size including 12 bits trellis termination (bits)	2220	13260	16716	18444	18444	18444	17484
Total number of bits per subframe	864	5184	12960	21600	43200	64800	86400
Total symbols per subframe	144	864	2160	3600	7200	10800	14400

5. LTE Product Development Challenges

The compressed timeline for LTE standards development has been mirrored by aggressive schedules for LTE product development. Successful proof-of-concept tests, trial networks, and test calls resulted in the launch of the first commercial services in late 2009 with wider rollout in 2010. As of May 2013, LTE networks were operating in more than 70 countries.

Nevertheless, the newness and the complexity of LTE has given rise to a number of product development challenges. Not least is the fact that LTE is an evolving standard, and as such, it is open to change and interpretation. From the technology perspective, a number of new techniques add substantial complexity. For example, the use of multiple antenna configurations to support high data rates makes the design of UE more complicated, as does the introduction of the SC-FDMA uplink modulation scheme. The "real-world" behavior of these enhancements is only now becoming understood and products optimized accordingly.

The six channel bandwidths specified for LTE, while increasing the flexibility and capability of the system, at the same time add to its overall complexity. Moreover, many LTE UE incorporate UMTS operating modes and as well as other wireless formats such as WiFi and *Bluetooth*®. Thus the ability to interwork seamlessly with other technologies is an important factor in determining LTE's success. The integration of the TD-SCDMA standard into the 3GPP specifications for LTE put a renewed emphasis on the development of systems with TDD capability. New components in the network architecture such as IP multimedia subsystems (IMS) and femtocells further add to the complexity.

Along with LTE-specific development challenges are those generally associated with designing products for emerging wireless systems. Product designs tend to be mixed-signal in nature, consisting of baseband and RF sections. Overall system performance depends on the performance of both categories, and each is associated with particular impairments—for example, non-linearities and effective noise figure in an RF up-converter or down-converter; phase and amplitude distortion from a power amplifier; channel impairments such as multi-path and fading; and impairments associated with the fixed bit-width of baseband hardware. With performance targets for LTE set exceptionally high, system engineers have to allocate resources to cover each critical part of the transmit and receive chain. Astute decisions regarding system performance budgets will be key in meeting system-level specifications as well as time-to-market goals.

An overview of LTE challenges and Keysight solutions are given here. However, much more extensive and in-depth coverage of these topics, with numerous test examples and illustrations can be found in the book LTE and the Evolution to 4G Wireless – Second Edition, ISBN: 978-1-1199-6257-1. This book is available from publisher John Wiley & Sons, Ltd.

5.1 Design simulation and verification

Design simulation tools help system engineers address LTE development challenges and verify their interpretations of the standard. Typically, models simulated at various levels of abstraction are needed to support the progression from product concept through detailed design. Performance of both base-band and RF sections must be evaluated individually and together to minimize the problems and surprises encountered during system integration and other phases of the development cycle. Finally, during the transition to hardware testing, a means of moving smoothly back and forth between design simulation and testing is needed to ensure that engineers are not forced to redesign the product on the bench to get it to work.

Figure 30 shows how an LTE system can be modeled and tested using Key-sight's connected solutions, which integrate simulation and test capability for verifying system-level performance with real device component hardware in the simulation path.

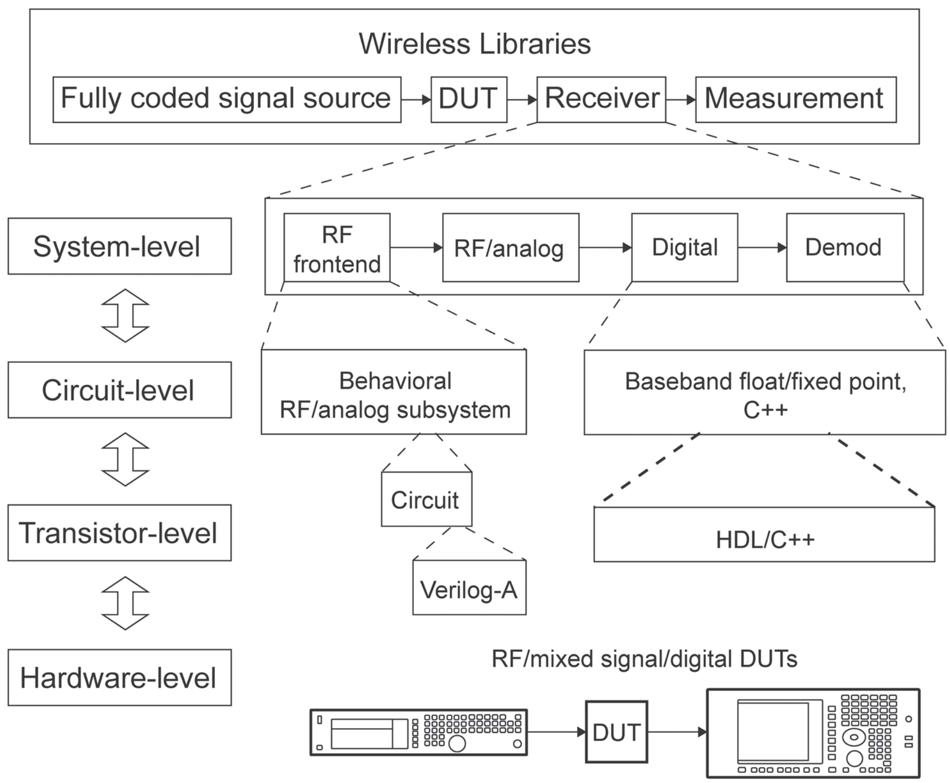


Figure 30. Simulation conceptual overview

5.1.1 Baseband design and verification

Keysight SystemVue is a powerful, electronic system level design environment for baseband PHY architectures and algorithms. SystemVue provides two levels of capability for LTE that bring instrument-like compliance to product designs at the earliest stages of development. First, SystemVue's baseband verification libraries offer pre-built LTE reference models that provide a "gold standard" to compare waveforms and generate test vectors at any point within a signal processing chain, down to the block level. The baseband verification libraries include compiled sources, receivers, function blocks, and reference designs that adhere to the physical layer of modern emerging standards. With native TCP/IP connectivity, the libraries also support co-design with test equipment and hardware development boards for both baseband and modulated-carrier signals.

Second, SystemVue's baseband exploration libraries go further to provide an open platform for innovative PHY designs that includes working, native source code for PHY blocks (math format) and documentation of the standards. Exploration libraries are polymorphic, incorporating compiled models for simulation speed, and are open to user-supplied IP for easy comparison. For designers working at the cutting edge of emerging standards, they a tremendous learning tool and productivity aid. See Figure 31.

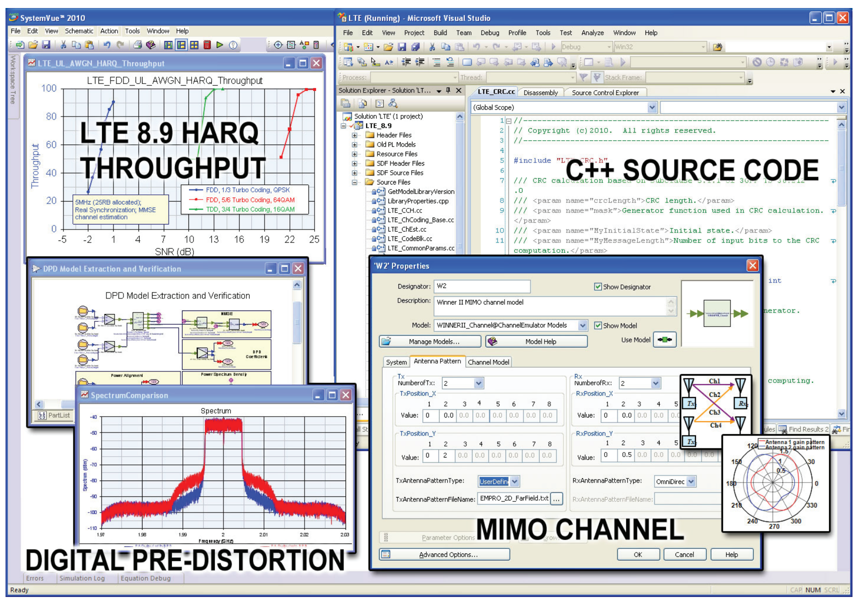


Figure 31. LTE simulation using SystemVue software

5.1.2 RF design and verification

Keysight's 3GPP LTE Wireless Library for the Advanced Design System (ADS) saves valuable design and verification time for RF designers and system integrators, and helps improve raw, uncorrected PHY performance. The 3GPP LTE Wireless Library provides signal processing models and preconfigured simulation setups for use within the ADS software. It creates and demodulates spectrally correct test signals that comply with the LTE specifications, including MIMO and TDD. This enables early verification of PHY performance of RF hardware before committing RFIC and board designs to fabrication, saving costly design turns. Designers can combine live, high-performance RF simulations, baseband simulations, and standards-compliant measurements from the real world to measure EVM, PAPR, CCDF, and ACLR performance of RF components.

5.1.3 Combining simulation and test hardware

At the hardware level, Keysight's simulation tools work seamlessly with test instruments to verify performance with actual device components added to the simulated model. For example, a simulated signal from SystemVue or ADS can be downloaded to a signal generator and effectively turned into a physical, real-world test signal. The test signal is run through the hardware device under test, and the device output is captured with a signal analyzer. The captured signal can then be read back into SystemVue or ADS for simulation post-processing.

Combining simulation with test provides even greater power and flexibility for hardware testing. For example, using the 89600 VSA software in simulation along with logic analyzers, digital oscilloscopes, and RF signal analyzers provides a common test methodology with a consistent user interface to help diagnose issues along the mixed-signal/RF transmitter/receiver chain (baseband, analog IQ, IF, RF). This powerful capability can be used to identify potential issues earlier in the cycle, when they are easier and less costly to fix. See Figure 32.

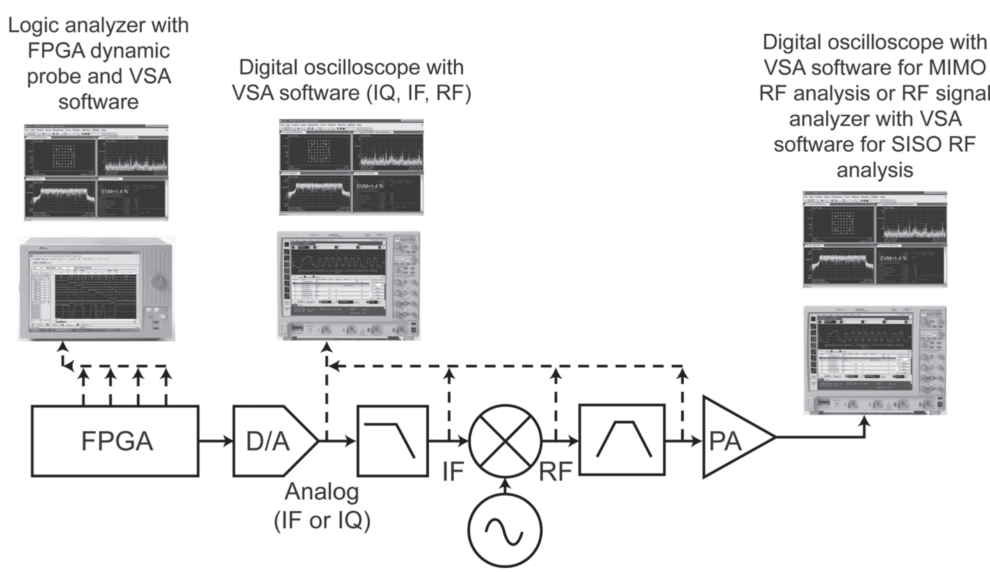


Figure 32. Troubleshooting a mixed-signal/RF transmitter chain

5.2 Uplink and downlink signal generation

Keysight has built a solid reputation in the mobile communications industry with the combination of signal generators and Keysight Signal Studio signal creation software. Signal Studio is available for the development and manufacturing of existing and evolving 2G through 4G communication systems. With this software, it is easy to create performance-optimized LTE reference signals for component-level parametric test, baseband subsystem verification, receiver performance verification, and advanced functional evaluation. See Figure 33.

Signal Studio software can be used with Keysight signal generators, which offer a wide range of performance from entry level to the industry's highest performance, with the Keysight MXG signal generator providing the best adjacent channel leakage ratio (ACLR), phase noise, output power, and more.

Signal Studio also can be used with the Keysight PXB MIMO receiver tester for applications that require MIMO fading, creation of interfering stimulus, digital I/Q inputs and outputs, real-time signal creation, or closed-loop testing of advanced LTE capabilities such as HARQ.

With these powerful tools users can create standards-compliant test signals for verification of conformance tests or custom signals for in-depth troubleshooting, and then marry this capability with the RF performance they require.

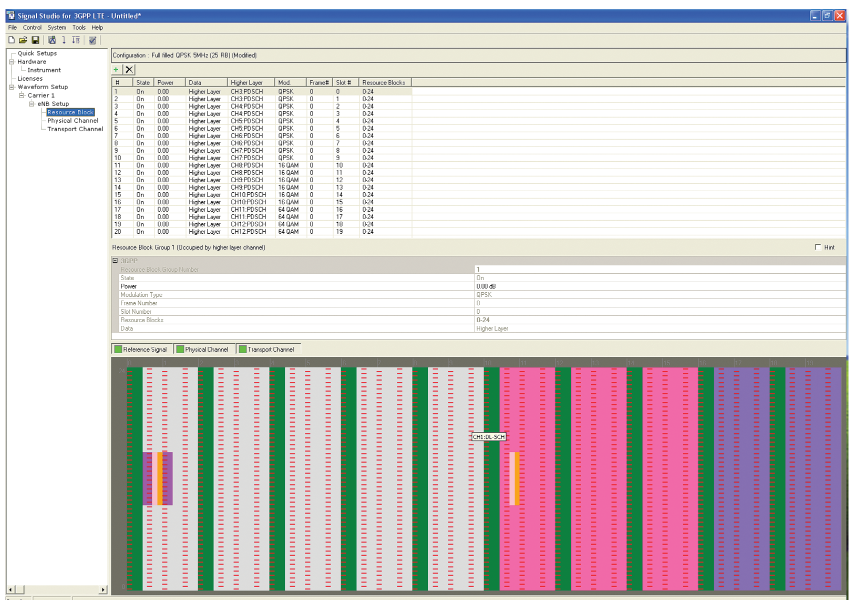


Figure 33. Resource mapping with scalable system bandwidth using Signal Studio software

5.3 Baseband analysis

5.3.1 Logic analysis

For both UE and base stations, the interconnect between the baseband and IF or RF subsystems has traditionally been analog, with some use of parallel digital systems, both of which come with a long history of probing and measurement techniques. However, with the peak data rates in wireless systems such as LTE continuing to increase, the analog and parallel digital interconnect methods cannot keep pace, and high speed serial interconnect is taking over. The use of serial interconnect, which can include embedded control, presents an entirely new domain for stimulation and measurement that demands next generation of test equipment.

Keysight is providing needed capability in its test equipment to meet these cross-domain test challenges. Figure 34 shows a typical LTE UE block diagram and the possible ways in which signals can be injected into or probed at different points to characterize the behavior of the device from baseband to antenna.

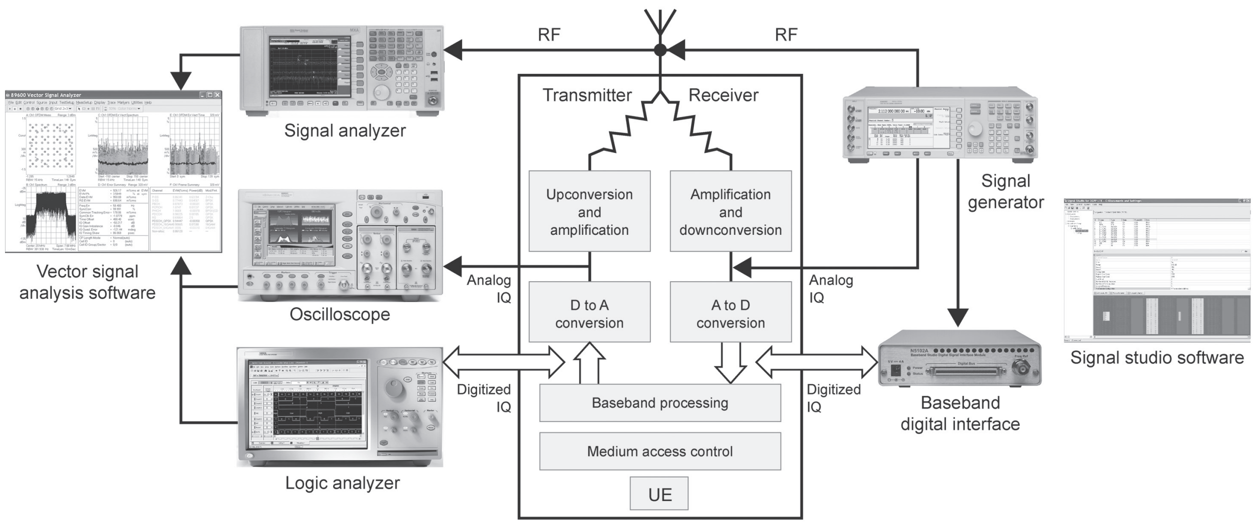


Figure 34. Cross-domain solutions for characterizing the behavior of devices from baseband to antenna, with access throughout the block diagram

The combination of a Keysight logic analyzer or radio digital cross domain (RDX) tester with Keysight 89600 VSA software creates a digital vector signal analysis package for digital baseband, IF, and RF signal analysis. This combination enables digital signal processing (DSP) designers to effectively design and debug interfaces that previously were analog and now are digital. The VSA software performs signal analysis functions such as I/Q analysis, EVM, and Fourier spectrum using the digital signal captured by the logic analyzer as the input.

To validate RF integrated circuit (RFIC) operation, engineers can also leverage the combination of signal generation software and the RDX tester connected to the system-under-test through a DigRF v3 or v4 high speed serial connection to test the transmit signal path.

5.3.1 Logic analysis (continued)

R&D engineers designing or integrating Mobile Industry Processor Alliance (MIPI™) D-PHY devices within a mobile handset can use the same logic analysis solution as a MIPI D-PHY and M-PHY protocol test solution with support for the DigRF v4, display serial interface (DSI), and camera serial interface (CSI) protocols. The solution includes a configurable stimulus platform that offers bit-to-video level test capabilities for embedded displays, real-time analysis, and protocol viewing capabilities. Engineers can gain valuable insight into the exchanges between MIPI D-PHY and M-PHY enabled devices.

5.3.2 Digital real-time decode and debug

Keysight high performance oscilloscopes work with the Keysight 89600 VSA software to analyze and debug wide bandwidth signals in LTE systems. For example, the Keysight Infiniium 9000 Q-Series scopes provide up to 33 GHz of analysis bandwidth and four phase-coherent channels ideal for 2x2 MIMO, 4x4 MIMO, and beamforming applications. Digitized signals are transferred from the scope to the 89600 VSA software, whose frequency, time, and modulation analysis tools can be used to evaluate and troubleshoot the signal.

5.3.3 DigRF access

For engineers using the DigRF (v3 or v4) baseband IC-to-RFIC interface, the Keysight RDX platform provides a comprehensive test solution that brings insight into both the digital and RF domains. The RDX platform allows engineers to work in either the digital or RF domain for digital protocol testing as well as RF (digital IQ) physical layer stimulus and analysis. The RDX platform integrates with the Keysight Infiniium scopes and RF portfolio to provide cross-domain solutions for deploying DigRF designs, aiding baseband and RFIC development, debug, and characterization. The RDX analyzer is shown in Figure 35.

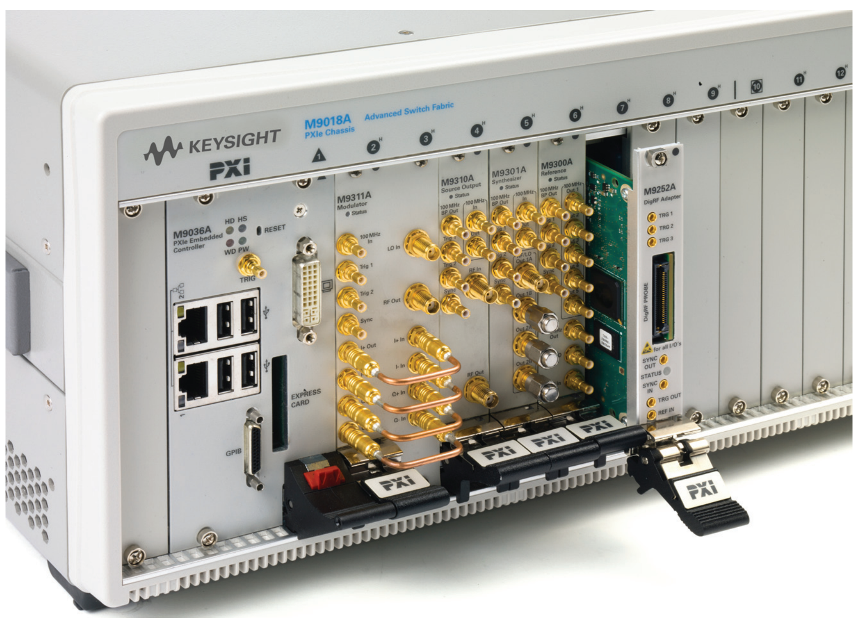


Figure 35. Test platform for access to DigRF v3 and v4 interfaces as well as digital IQ data

5.4 Uplink and downlink signal analysis

The complexity of LTE systems requires signal analysis with in-depth modulation analysis as well as RF power measurements. The Keysight X-Series (PXA/MXA/EXA) signal analyzers make it easier to measure complex signals by providing world-class accuracy, repeatability, and standards-compliant measurement applications. In combination with the 89600 VSA software, the X-Series signal analyzers provide sophisticated general-purpose and standards-compliant signal evaluation and troubleshooting tools for R&D engineers.

For RF and baseband engineers, the 89600 VSA software with LTE analysis capability offers the industry's most comprehensive LTE physical layer signal analysis. The software includes downlink (OFDMA) and uplink (SC-FDMA) in a single option. Both FDD and TDD operating modes are covered, as are all LTE bandwidths, from 1.4 MHz to 20 MHz. All modulation formats and sequences are included: BPSK, QPSK, 16QAM, 64QAM and CAZAC (Zadoff-Chu). The 89600 VSA software supports up to 8x8 DL MIMO with supported 4-channel platforms. A rich selection of in-channel measurements and traces includes overall/data/RS EVM, EVM per channel, carrier, symbol, resource block and slot. The software's well-designed user interface provides up to six simultaneous, user-selected displays, color coding, and marker coupling among multiple traces.

An example of downlink signal analysis using the 89600 VSA software is shown in Figure 36.

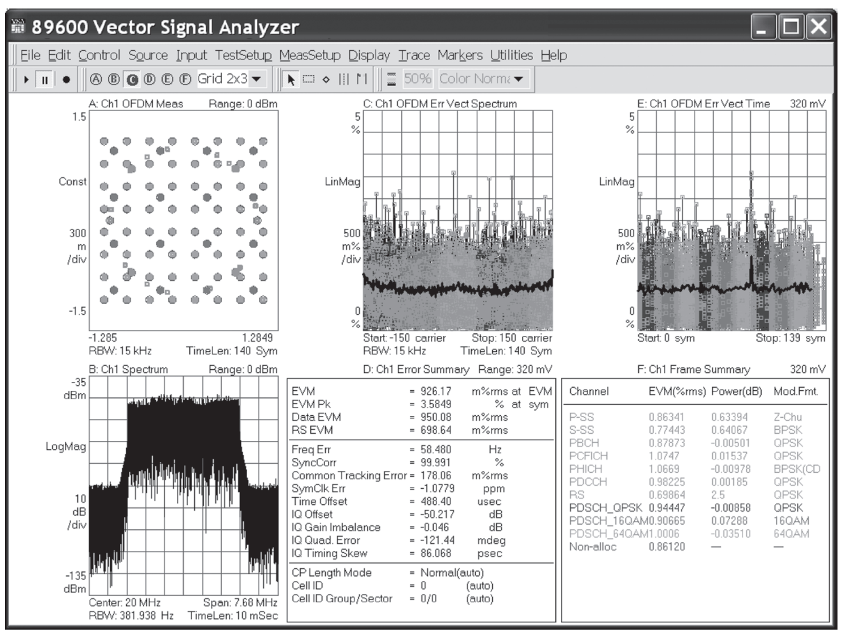


Figure 36. Analysis of digitally demodulated 5 MHz LTE downlink signal using 89600 VSA software

5.5 UE development

5.5.1 UE development test set

The Keysight PXT E6621A LTE wireless communications test set is shown in Figure 37. For faster, more efficient UE development, the PXT incorporates flexible base station/network emulation and RF parametric tests into one integrated unit. The PXT includes a suite of LTE RF measurements for the UE uplink (transmitter) and UE downlink (receiver) that may be used for characterization, calibration, and verification purposes.

With realistic base station/network emulation, the PXT LTE test set offers a controlled environment which can be used to provide network signaling to verify UE functional performance such as throughput. The PXT provides maximum flexibility to configure a range of connection and network parameters. This enables test, stress, and debug of the protocol and data handling capabilities of designs including circuit switched fall back (CSFB), simultaneous voice and LTE (SVLTE), and single radio voice call continuity (SRVCC).

Optional software applications are available for more detailed protocol and application testing and analysis.

Figure 37. Keysight PXT wireless communications test set for signaling protocol and RF parametric test

5.5.2 UE signaling protocol test systems

Given the complexity of the LTE UE, successful products rely on a program of testing that goes beyond the minimum requirements of the standards. As part of such a test program, the stability of the software in the UE needs to be the subject of relentless and systematic test. That includes the signaling software, which is a major contributor to the overall stability of the UE. The work of UE developers who are creating or enhancing protocol stacks focuses on the development and testing of new features including the interactions with legacy features, and regression testing of legacy features in the new product.

A comprehensive signaling protocol test system is based on the E6621A PXT LTE test set used in conjunction with the E5515A 8960 2G/3G test set. The PXT is able to operate with self-contained base-station protocol emulation for high performance signaling operation. The PXT and the E5515A/8960 test set together can emulate non-LTE multi-RAT environments. The 8960 is able to support a large variety of GERAN, UTRAN, and cdma2000 cell configurations. The PXT and E5515A/8960 work with external Keysight software including message editor and protocol logging and analysis applications to capture and replay multi-layer protocol logs.

5.5.3 UE interactive functional test system

Keysight's Interactive Functional Test (IFT) software is designed to utilize the industry-leading signaling and data capabilities of the Keysight E6621A PXT wireless communications test sets. The IFT provides a solution for real-world functional test of LTE mobile devices. Engineers can bring real-world test into the design cycle earlier by automating and simplifying design, verification, stress test, and realistic user-experience scenarios.

- System configuration wizard
- Easy and flexible set up of operations
- Ability to perform operations simultaneously (just as an end-user would)
- Easy script development for test sequence repetition

The IFT software provides a highly productive way for test engineers to run complex functional test scenarios that measure the impact of stresses on UE performance. A good example is battery drain analysis, shown in Figure 38.

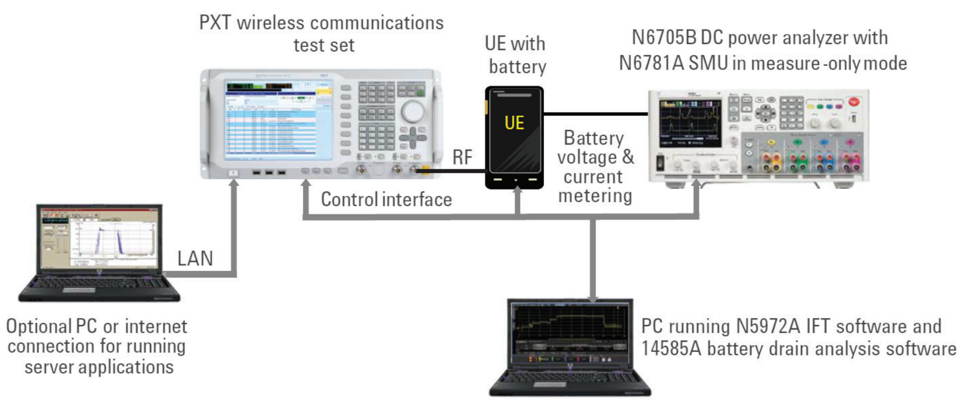


Figure 38. Example configuration for funtional test with battery drain analysis

5.5.4 UE battery drain testing

Although advances in battery capacity continue to be made, they are being outpaced by the demands of modern UE. It is not just the primary radio that requires power; power is required by multiband multi-RAT support, receive diversity, MIMO, interference cancellation, ever-higher data rates, Wi-Fi, *Bluetooth*, FM Radio, MP3, MP4, GPS, larger brighter displays and, in the not so distant future, integrated video projection. Installing a larger battery is usually not an option; consequently, an increasing amount of R&D effort has to be directed towards designing, measuring, optimizing, and verifying UE current consumption in an ever wider set of use cases. The task of analyzing battery current drain can be made much easier with the use of advanced tools.

The Keysight 66319D/66321D and N6781A are DC source/measurement units were designed specifically for wireless device current drain testing. The DC sources can be used as battery emulators or in a special zero voltage configuration to measure the performance of the mobile device battery, commonly called battery run down testing. The 66319D/66321D DC sources are used in conjunction with the Keysight 14565B battery drain analysis software, enabling the designer to carry out advanced current drain analysis either manually or with full automation at all stages of the product design lifecycle. The N6781A is used in the N6705B DC power analyzer mainframe with advanced current drain analysis, which can be further enhanced using the optional 14585A software. Three basic measurement modes are supported:

- Waveform mode provides an oscilloscope-like capability for capturing and analyzing current drain signals from tenths of milliseconds to seconds in duration.
- Data logging mode provides extended current drain measurement and analysis for up to 1,000 hours of testing.
- Complementary cumulative distribution function (CCDF) mode provides statistical profiling to display current drain performance for up to 1,000 hours operation.

5.6 UE conformance test

The T4010S conformance test (CT) system shown in Figure 39 is the Keysight solution for LTE RF conformance testing of LTE UEs and is part of the T4010S family of automated RF testers. The T4010S CT is targeted at laboratories within UE and chipset manufacturers and third party certification test houses. It provides a comprehensive set of tools that help the user through the process of entering device under test (DUT) data into the test system, defining the test plan to be executed, configuring the system to execute the tests according to the specific UE characteristics and finally, analyzing the tests results and producing the associated test reports.

The validation status over an increasing number of bands and the support of GCF (Global Certification Forum) and PTCRB (PCS Type Certification Review Board) specific requirements, together with the complete test system automation capabilities and reduced overall footprint, make the T4010S CT the most competitive test platform to have in any laboratory environment.

Keysight T4010S family of test systems also includes the T4010S DV, which provides LTE UE manufacturers with design verification parametric RF testing and pre-conformance capabilities. Since all systems within the T4010S family share the same underlying hardware and software platform, CT and DV versions can coexist on the same test system for maximum convenience and cost-effectiveness.

Figure 39. RF conformance test system for LTE UEs

5.7 UE manufacturing test

Wireless technologies are evolving rapidly and more wireless bands and formats are being implemented on chipsets, smartphones, and other wireless communication devices. Manufacturers are looking for fast and cost-effective ways to produce these complex devices. Reducing the time and cost of test will go a long way toward achieving this goal.

Non-signaling is widely accepted as the fastest, most cost-effective technique for testing next-generation wireless devices in manufacturing. By taking advantage of test modes built into the new chipsets, non-signaling test can eliminate costly signaling overhead from the manufacturing test process, increasing throughput while maintaining the integrity of the test and quality of the finished product.

The Keysight EXT is designed and optimized for non-signaling test in wireless device manufacturing. The EXT's integrated hardware and innovative, industry-leading software tools provide the fastest route from pre-production through high-volume manufacturing.

The integrated one-box test set combines a vector signal analyzer, vector signal generator, test sequencer, multiport adapter, and modern, scalable platform. Fast measurements and flexible sequencer techniques work in synch with your device's chipset test modes to execute test plans at the highest speed for maximized throughput. Unique, graphical Sequence Studio software dramatically streamlines test plan creation and troubleshooting, saving code development time to move from NPI to volume manufacturing. Fast, standards-based measurements and modulation analysis capability are based on proven Keysight X-Series measurement algorithms, so that new formats can be added quickly. See Figure 40.

The E6617A multiport adapter expands the E6607B EXT's capacity to eight fully calibrated RFIO interfaces and four GPS ports, enabling parallel device testing, dramatically increasing the production throughput, and further reducing the cost of test. In the E6607C EXT, the multiport capability has been integrated into the one-box tester. The EXT tests new and existing radio formats including LTE TDD/FDD, W-CDMA, HSPA+, cdma2000/1xEV-DO, TD-SCDMA, *Bluetooth*, WiMAX™ and more.

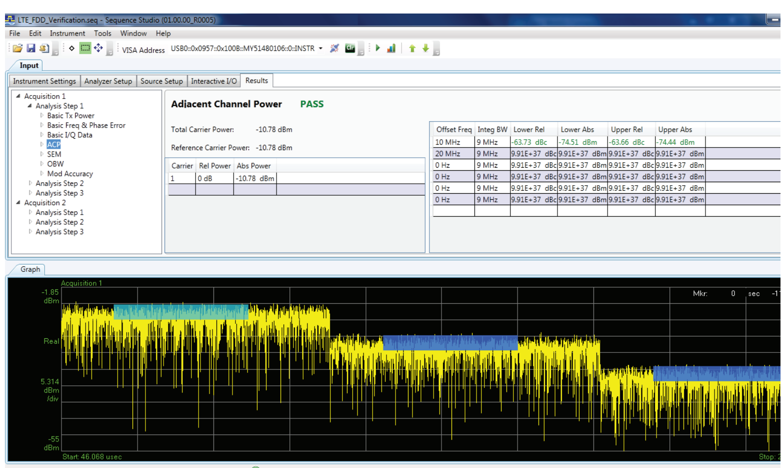


Figure 40. Keysight EXT with Sequence Studio software provides fast sequencing to optimize manufacturing test plans

5.8 Network deployment and optimization

The Keysight FieldFox RF analyzer (4 GHz/6 GHz) is a highly integrated, fast, and rugged handheld RF analyzer for wireless network installation and maintenance. This six-in-one RF tester combines cable and antenna analysis, spectrum analysis, interference analysis, power meter measurement, vector network analysis, and a vector voltmeter into one rugged, compact, lightweight, and weather-resistant package, shown in Figure 41. FieldFox supports power suite measurements for LTE as well as for GSM and W-CDMA.

For LTE testing, one-button GSM/WCDMA/LTE power measurements make Node B transmitter tests much easier and worry free. LTE TDD spectrum analysis power measurement enables identification of uplink interference during network operation.

FieldFox has exceptional speed of 1.5 updates per second in the commonly used 20 MHz span and the 3 kHz resolution bandwidth. The handheld analyzer offers the best dynamic range in spectrum analyzer mode (96 dB) and the fastest sweep times for interference detection with resolution bandwidths under 30 kHz.

FieldFox meets current and future wireless network installation and maintenance challenges with superior performance in all measurements. The tester's interference analyzer option allows test engineers to detect intermittent signals more quickly using the built-in spectrogram and waterfall display along with record and playback functions.

An integrated QuickCal capability is used to calibrate the instrument without a calibration kit for worry-free accuracy and repeatability, and a CalReady feature makes the tester calibration-ready at the test port immediately after power-up.

Figure 41. Handheld RF analyzer that combines the functions of six instruments in one integrated, fast, and rugged package

6. Conclusion

The launch of LTE is changing the wireless industry. Subscribers are taking advantage of the higher data rate services enabled by LTE, and overall data usage is climbing. As the industry continues to move toward LTE-Advanced and “true” 4G technology, it will continue to require measurement solutions that keep pace with the standard’s development.

In the measurement domain, Keysight is at the forefront with design automation tools and flexible instrumentation for early R&D in components, base station equipment, and mobile devices. Keysight continues to provide a leadership role in defining essential test strategies and providing a broad, comprehensive portfolio of solutions that address the entire LTE product development life cycle—from early design through to production test and deployment. LTE may present many development challenges, but with early and powerful test equipment solutions, these challenges are being met.

7. More Information

For more information about the 3GPP, visit the 3GPP home page
http://www.3gpp.org/

3GPP specifications home page
http://www.3gpp.org/specifications

3GPP Series 36 (LTE) specifications
http://www.3gpp.org/ftp/Specs/html-info/36-series.htm

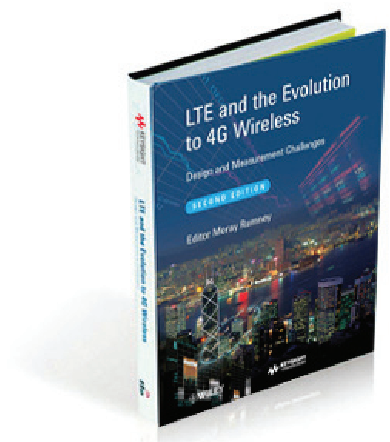
For more information about Keysight design and test products for LTE visit
http://www.keysight.com/find/lte

For more information about LTE-Advanced (3GPP Release 10 and beyond) and Keysight LTE-Advanced test solutions
http://www.keysight.com/find/lte-advanced

Learn more about LTE and its measurements in the new book written by 42 LTE experts:

From both a technical and a practical point of view, there is still much to examine, evaluate and understand in 3GPP LTE cellular technology and the evolution to LTE-Advanced. The first edition of this book, with content from Keysight engineers and other industry experts, covered basic concepts such as OFDMA, MIMO and SC-FDMA. This second edition, with over 42 authors, is updated to the latest 3GPP standards, June 2012 and Release 11, and looks forward to Release 12.

LTE and the Evolution to 4G Wireless
Design and Measurement Challenges, second edition



http://www.keysight.com/find/ltebook

8. List of Acronyms

3GPP	3rd Generation Partnership Project
ACLR	Adjacent channel leakage ratio
ACS	Adjacent channel selectivity
ADS	Advanced Design System
AMC	Adaptive modulation and coding
A-MPR	Additional maximum power reduction
AoA	Angle of arrival
ARQ	Automatic repeat request
BCCH	Broadcast control channel
BER	Bit error ratio
BLER	Block error ratio
BTS	Base transceiver station
CCDF	Complementary cumulative distribution function
CDMA	Code division multiple access
CFI	Control format indicator
CP	Cyclic prefix
CPICH	Common pilot channel
CQI	Channel quality indicator
CRC	Cyclic redundancy check
CSFB	Circuit switched fall back
DCI	Downlink control indicator
DFT	Discrete Fourier transform
DFT-SOFDM	Discrete Fourier transform spread OFDM
DL	Downlink (base station to subscriber transmission)
DL-SCH	Downlink shared channel
D-PHY	500 Mbps physical layer
DRX	Discontinuous reception
DSP	Digital signal processing
DUT	Device under test
DVSA	Digital vector signal analysis
DwPTS	Downlink pilot time slot
E-DCH	Enhanced dedicated channel
EDGE	Enhanced data rates for GSM evolution
EMC	Electromagnetic compatibility
eNB	Evolved node B
EPC	Evolved packet core
EPRE	Energy per resource element
EPS	Evolved packet system
E-TM	E-UTRA test model
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UMTS terrestrial radio access
E-UTRAN	Evolved UMTS terrestrial radio access network
EVM	Error vector magnitude
FDD	Frequency division duplex
FDMA	Frequency division multiple access
FEC	Forward error correction
FFT	Fast Fourier transform
FRC	Fixed reference channel
GCF	Global Certification Forum
GERAN	GSM enhanced radio access network
GPRS	General packet radio system

GSM	Global system for mobile communication
GW	Gateway
HARQ	Hybrid automatic repeat request
HeNB	Home evolved node B
HI	HARQ indicator
HNB	Home node B
HRPD	High rate packet data
HSDPA	High speed downlink packet access
HSPA	High speed packet access
HSUPA	High speed uplink packet access
ICS	Implementation conformance statement
IFFT	Inverse FFT
IFT	Interactive functional test
IMS	IP multimedia subsystem
IP	Internet protocol
LO	Local oscillator
LSTI	LTE/SAE Trial Initiative
LTE	Long term evolution
MAC	Medium access control
MBMS	Multimedia broadcast multicast service
MBSFN	Multicast/broadcast over single-frequency network
MCH	Multicast channel
MIMO	Multiple input multiple output
MISO	Multiple input single output
MME	Mobility management entity
M-PHY	M physical layer
MPR	Maximum power reduction
MSR	Multi-standard radio
MU-MIMO	Multiple user MIMO
NAS	Non-access stratum
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
OTDOA	Observed time difference of arrival
PAPR	Peak-to-average power ratio
PAR	Peak-to-average ratio
PBCH	Physical broadcast channel
P-CCPCH	Primary common control physical channel
PCFICH	Physical control format indicator channel
PCH	Paging channel
PDCCH	Physical downlink control channel
PDCP	Packet data convergence protocol
PDSCH	Physical downlink shared channe
P-GW	Packet data network gatewayl
PHICH	Physical hybrid ARQ indicator channel
PHY	Physical layer
PRACH	Physical random access channel
PMCH	Physical multicast channel
PMI	Pre-coding matrix indicator
PTCRB	PCS Type Certification Review Board
PUCCH	Physical uplink control channel
PUSCH	Physical uplink shared channel

8 List of Acronyms *(Continued)*

QAM	Quadrature amplitude modulation
QPSK	Quadrature phase shift keying
RACH	Random access channel
RAT	Radio access technology
RB	Resource block
RDX	Radio digital cross domain
RE	Resource element
RF	Radio frequency
RFIC	Radio frequency integrated circuit
RI	Rank indication
RLC	Radio link control
RMC	Reference measurement channel
RNC	Radio network controller
RRC	Radio resource control
RRM	Radio resource management
RS	Reference signal
RSCP	Received signal code power
RSRP	Reference signal received power
RSRQ	Reference signal received quality
RSSI	Received signal strength indicator
RSTD	Reference signal time difference
RTT	Radio transmission technology
SAE	System architecture evolution
SAP	Service access point
SC-FDMA	Single carrier frequency division multiple access
SFBC	Space-frequency block coding
S-GW	Serving gateway
SIMO	Single input multiple output
SISO	Single input single output
SNR	Signal-to-noise ratio
SRS	Sounding reference signal
SRVCC	Singe radio voice call continuity
SU-MIMO	Single user MIMO
TADV	Timing advance
TDD	Time division duplex
TM	Transmission mode
TDMA	Time division multiple access
TD-SCDMA	Time division synchronous code division multiple access
TR	Technical report
TrCH	Transport channel
TS	Technical specification
TTA	Telecommunications Technology Association
UCI	Uplink control indicator
UE	User equipment
UL	Uplink (subscriber to base station transmission)
UL-SCH	Uplink shared channel
UMTS	Universal mobile telecommunications system
UpPTS	Uplink pilot time slot
UTRA	Universal terrestrial radio access
UTRAN	Universal terrestrial radio access network
VSA	Vector signal analysis
W-CDMA	Wideband code division multiple access

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